# REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188



1. AGENCY USE ONLY ( Leave Blank)

2. REPORT DATE
1 Sept. 2001

3. REPORT TYPE AND DATES COVERED
Final 30 Sep 1999 - 29 Sep 2001

4. TITLE AND SUBTITLE
Phase II Final Report: Actuator for Out-of-Plane MEMS Devices

5. FUNDING NUMBERS
C- N00167-99-C-0093

6. AUTHOR(S)
Dr. A. David Johnson, Vikas Gupta

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TiNi Alloy Company
1619 Neptune Drive
San Leandro, CA 94577

8. PERFORMING ORGANIZATION REPORT NUMBER
NA

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Caderock Division
Naval Surface Warfare Center
9500 MACARTHUR Blvd.
West Bethesda, MD 20817-5700

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; SBIR Report, distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Two major problems from phase I were solved during phase II. The step-coverage problem of TiNi thin film on the polysilicon structure was solved by introducing silicon-on-insulator (SOI) wafers. Also the out-of-plane devices were fabricated completely in-house to eliminate the problem of long turn-around time at the Microelectronics Center of North Carolina (MCNC). In a novel approach, the micromirrors were fabricated from the thin silicon membrane layer of the SOI wafer. Hinge structures were fabricated from SU-8 photoresist. Since the mirrors and the actuator beams were made on same silicon plane, the sharp step and thus the problem of step-coverage was eliminated. TiNi thin film was sputter deposited on silicon beams to form actuators. Silicon oxide and OCG 825 photoresist were used as sacrificial layers for releasing the mirrors and hinges respectively. The mechanical functionality of hinges made in-house was verified and demonstrated by tilting the silicon mirrors from horizontal to vertical position.

Magnetic actuation was investigated as an alterative method for actuating the mirrors. A magnetic alloy, Permalloy, was successfully plated on the spacer dies from MCNC. Spacer devices were chemically released from the substrate and tested for the actuation. Displacement of the released spacer devices magnetically was demonstrated.

14. SUBJECT TERMS
fiber optic switch, micromirrors, shape memory alloy, TiNi thin film, actuator, Permalloy

15. NUMBER OF PAGES
54

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OR REPORT | 18. SECURITY CLASSIFICATION ON THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500

**Standard Form 298 (Rev.2-89)**
Prescribed by ANSI Std. 239-18
298-102

## TABLE OF CONTENTS

## LIST OF FIGURES

## List of Tables

## 1.0 INTRODUCTION

As a continuation of Phase I research work, this project is intended to find an innovative solution to a critical problem: maintaining a stable distance between the front and back planes in large evacuated flat-panel displays. Support is necessary because atmospheric pressure distorts the front and back plane surfaces. The proposed solution consists of placing many small column-type structures between the surfaces to hold them apart at a precise distance of about 200 μm .

The columnar structures are to be placed between the pixels. These structures are to be fabricated in the plane of the field-emitters and raised to vertical position by microactuators of titanium-nickel (TiNi) thin film shape memory alloy (SMA) attached to each beam. Residual tensile stress developed in TiNi from the annealing process is used as the actuation force to raise the structures. A latching mechanism is incorporated in order to hold the structures in upright position.

During the Phase I research work, mechanical designs of spacers were developed using surface micromachining technology. Hinges, latches, spacers and actuators were fabricated. The principal problems encountered in Phase I were: 1) step coverage of TiNi thin film, and 2) long device turn-around time from the Microelectronics Center of North Carolina (MCNC) foundry. To solve these problems, in Phase II, devices were redesigned in order 1) to eliminate sharp steps and 2) to investigate other actuation mechanisms, for example magnetic actuation, and 3) be able to fabricate devices fully in-house.

In the initial part of Phase II, devices were fabricated using ferromagnetic material to provide magnetic actuation. Plating of ferromagnetic material on MCNC devices was successfully achieved. Devices were released and actuated magnetically. In the final part of Phase II, in order to solve the problems of step-coverage and long lead time at the MCNC foundry, devices based on new designs were fabricated and tested at TiNi Alloy Company.

## 2.0 SUMMARY

In the manufacture of field emission displays (FEDs) it is necessary that the front and back panels of the vacuum envelope be held a fixed distance apart against atmospheric pressure. The spacers used must be insulating, strong, machined with extreme precision, chemically clean, and small enough to fit between the pixels. This project is devoted to the development of micromachined hinged spacers of polysilicon that are fabricated in the plane of the emitters and erected just prior to assembling the vacuum envelope.

In Phase I, hinged structures were fabricated using MCNC MUMPS (Multi-User MEMS Processes). Thin film TiNi SMA was sputter deposited on the surface of these dies, patterned, and etched to form actuators. The actuators were then released. Use of HF to etch silicon oxide was found to damage TiNi, so other etchants were investigated, and a successful procedure was found.

The major problem encountered was with step coverage where TiNi was deposited over the edges of the hinge. It was not immediately clear that the step was not covered as the sputter deposited TiNi appeared continuous in an optical microscope. It was only after examining the cross-sections of specimens by use of an SEM (scanning electron microscope) that the problem became understandable. Step coverage can be improved by biasing the substrate during deposition, by substrate heating, and by motion of the substrate relative to the target. Yet another approach is to move the plasma with rotating magnets during deposition. All of these modifications were implemented but did not work well. Therefore, in Phase II the design was modified to eliminate the problem of step coverage.

In Phase II, SU-8 photoresist was used as part of the structure in order to be able to make hinges without use of the MCNC facility. This decision was taken because MCNC dies are limited to 1 cm in size, the processes used are too costly for manufacture, the dies have limited thickness of polysilicon, and the delay between submission of an order and receipt of devices is several months, which severely limits the number of experiments that can be conducted.

The requirements imposed, as stated above, demand a novel approach to the spacer problem. The concept of hinged elements that are slender enough to be optically invisible but strong enough to resist the force of atmospheric pressure, has been validated. Two methods of actuation have been evaluated: 1) use the inherent strength and high work output of TiNi shape memory thin film to accomplish erection of spacers, or 2) make the hinged spacers magnetic and use magnetic force to bring them to a vertical position.

This latter method requires plating of magnetic material onto the surface of the spacer. The spacer is coated with FeNi, (trade named "Permalloy,") then the spacer is released, and an external permanent magnet is passed over the substrate to raise all spacers simultaneously. This has been successfully demonstrated using MCNC dies.

In recent years other display technologies have advanced more rapidly to production than FEDs. Stanford Resources presented a Flat Information Display Conference in Monterey December 1999. Competitors to FEDs include organic light emitting diodes, plasma display panels, gas plasma monitors, and several forms of liquid crystal displays. Reflective displays, especially Texas Instruments' digital light processing (DLP) technology are enjoying wide acceptance. Field emission display technology has many advantages over competing technologies--low power consumption and high luminosity being the foremost. Although many companies are developing FEDs, they are not yet market leaders. Presenters at the conference included Stewart Hough (Candescent Technologies), and Jim Cathey (PixTech).

The two approaches taken (actuation by TiNi SMA thin film and magnetic levitation) can both be combined with manufacturing processes used in the manufacture of FEDs. See patent number 5,903,099, Fabrication System, Method and Apparatus for MicroElectroMechanical Devices; Johnson, Busta, Nowicki; May 1999.

## 3.0 CONCLUSIONS AND EVALUATIONS OF PHASE I RESULTS

In Phase I, the use of TiNi SMA thin film microactuators, which can produce large displacements in a small space with significant force, was proposed. Microdevices of several designs were fabricated at MCNC. After the microdevices were received from MCNC, TiNi thin film was deposited and patterned. TiNi thin film was resistively heated to bring the SMA microribbons to actuation temperature.

In Phase I the following goals were successfully met:

- TiNi actuated thin film SMA, as small as a few microns, were fabricated.
- Ten micron-size TiNi thin film SMA devices were shown to exhibit phase transformation and shape-memory effect.
- TiNi thin film SMA devices were electrically actuated.
- Functional, mechanically strong, hinged structures were fabricated, and TiNi SMA thin film deposited on the surface. Locking mechanisms were incorporated to hold the spacers upright.
- Micromachined hinged structures demonstrated sufficient strength to withstand atmospheric pressure.
- All the individual processes necessary for fabrication of spacers were demonstrated to be feasible.
- Composite beams (bimorphs) were actuated by differential thermal expansion, giving substantial deflection with long lifetime.
- Facilities for inspection and manipulation of microdevices, and recording of data, were significantly improved.
- Finally, it was shown that Si-TiNi composite beams could be actuated by contraction of TiNi during phase transformation, thus demonstrating the mechanism on which this project was based.

These accomplishments provided a foundation for continuation into Phase II. The mechanical design developed was used with minor changes in the next generation of devices. The principal problem encountered in Phase I was step coverage during sputter deposition of TiNi thin film: this was the first item of business in the continuation of the work. Improved in-house facilities including SU-8 processes, and use of local vendors for deposition of polysilicon, silicon oxide, silicon nitride and deep reactive ion etching (DRIE) reduced time for completion of experimental cycles.

The proposed research program utilized two existing technologies in order to accomplish a novel purpose with great commercial potential: surface micromachining and shape-memory film actuators.

## 4.0 OBJECTIVE OF PHASE II WORK

The ultimate objective of Phase II was to fabricate and demonstrate a working model of a spacer device that can be incorporated in flat panel field emission displays. Phase I research had relied on MCNC polysilicon technology. Figure 1 shows some of the structures received from MCNC. Dependency on MCNC proved to be a major problem during Phase I. Their lead time to fabricate and deliver the devices was long, delaying time between iterations. Limitations imposed by the MCNC-MUMPS process also impeded our work. Therefore, we decided to establish capability to fabricate spacers in-house, independently of MCNC-MUMPS.

The method of actuation also received attention during Phase II. A decision was made to make a trial of magnetic actuation by tilting the slender beams from a horizontal to a vertical position using magnetic force. A few of the old MCNC dies were available for this purpose. A ferromagnetic material, Permalloy (78 % Ni- 22 % Fe), was selected for this purpose and was sputtered on top of the long, slender, polysilicon beams on the MCNC dies (shown in Figure 2).

To solve the problem of step coverage, new designs of spacers were developed and fabricated. Materials like silicon-on-insulator (SOI) wafers and SU-8, a high aspect ratio photoresist, were introduced in the devices.

To accomplish Phase II objectives the following tasks were performed:

- The feasibility of using a magnetic actuation mechanism in which the problem of step coverage does not occur was explored.
- A process to deposit magnetic material on spacer devices was developed.
- The actuation of more than one spacer to a vertical position using magnetic actuation was demonstrated.
- New designs of spacer devices capable of being fabricated using in-house facilities, made of other than polysilicon material (for example SU-8 and SOI wafer) were developed.
- The process sequence to fabricate silicon based spacers and SU-8 based hinge structures and also to release the spacers and hinges was developed.
- The tilting of spacers from horizontal to vertical position was demonstrated.

## 5.0 PROGRESS/ACCOMPLISHMENTS IN PHASE II

### 5.1 Magnetic Actuation

The proposed objective of this research effort was to fabricate miniaturized long and slender blocks of material that lie in the street between the pixels of a flat panel display. When these slender blocks are rotated out-of-plane using a method like shape memory alloy actuation or magnetic actuation, they act as spacers between two glass plates.

For Phase II, a decision was made to try magnetic actuation to actuate the slender beams as a possible alternative to shape memory actuation and also as a solution to the problem of step coverage. A few of the old MCNC dies were available to test magnetic actuation. Permalloy was selected to be sputtered on top of the long, slender, polysilicon spacer beams on the MCNC dies (shown in Figure 1).

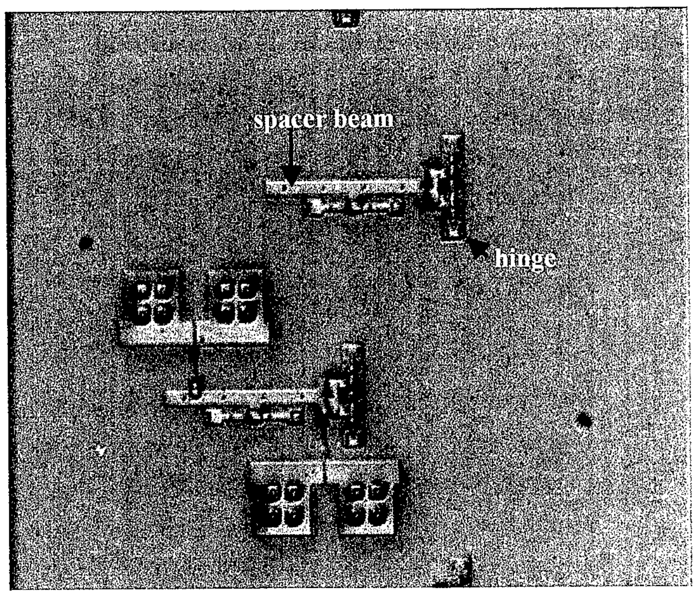


Figure 1: Hinged spacer beams fabricated of polysilicon. The spacer is 200 μm long and approx. 40 μm wide.

Once Permalloy was deposited on top of these beams, they were released. The spacers were actuated magnetically to rotate at 90° by passing a strong magnet at a small distance from the top of the silicon die.

Permalloy can be deposited onto a substrate either by sputtering from a source or plating. Both approaches were considered. Sputtering targets were ordered and received from Target Materials, Inc. Initially, a set of calibration experiments with sputtering were performed to bring the process on line. Difficulty was encountered because of the magnetic characteristics of the material which interfere with the D.C. magnetron sputter. Meanwhile attempts were also made to plate Permalloy using a nickel sulfate plating solution composed primarily of nickel sulfate, ferrous sulfate as the source of iron ions, and boric acid as the buffer [1,2,3]. Plating was carried out at 50°C. The deposition rate was approx. 0.25 μm per minute, calculated on a dummy sample. The percentage of nickel and iron has not been checked in the plated samples. A magnet was used to see if small dies plated with Permalloy could be actuated. On bringing a small magnet close to the plated die, the die became attached to the magnet confirming that the plated material was indeed ferromagnetic.

Encouraged by the initial success of plating a ferromagnetic material, it was decided to plate the Permalloy on top of the leftover MCNC dies (1cm x 1cm in size).

Two types of experiments were planned:

In the first type of experiment, the slender beams of polysilicon were still attached to the base substrate. Silicon oxide was the sacrificial layer to be etched after plating Permalloy to release the polysilicon beams. These dies were sputtered with a 0.5 μm nickel layer as a base-plating layer. The plating was initiated on top of these first types of dies. Permalloy was plated for 5 minutes, 10 minutes and 15 minutes. Attempts were made to release the slender beams using a 50% solution of HF and glycerin. A micromanipulator was used to inspect whether the spacers had been released. None of the beams on these dies were found to be released. We believe that the plated nickel had covered the edges of the beams and would not allow access for HF to attack the silicon oxide sacrificial layer.

To eliminate this problem, in the second experiment, the slender polysilicon beams were partially released in a 50% solution of HF prior to sputtering and plating. Since HF is an aggressive etchant, the etching time was very critical. An excess of a few seconds in HF can lead to a full release of a device after which the die can not be used for sputtering and plating. After partial release, the die was sputtered with a 0.5 μm thick nickel base-plating layer in a Perkin Elmer PE4400 sputtering system. Permalloy was then plated for 3 minutes on the die, resulting in a 0.75 μm thick layer of plated magnetic material all over the die. After plating the Permalloy on the partially pre-released devices, the dies were then immersed in HF 48% solution to release the remaining part of the spacers. This time, the spacers released fully in HF solution. The die with fully released devices was placed on a micromanipulator chuck. Double-sided adhesive tape was used to hold the die in place. When a small but strong magnet was passed through over one of the die, the released spacers, under the magnetic force, immediately moved from horizontal to vertical position. Figures 2 through 7 illustrate microfabrication and actuation of the spacer beams in succession.

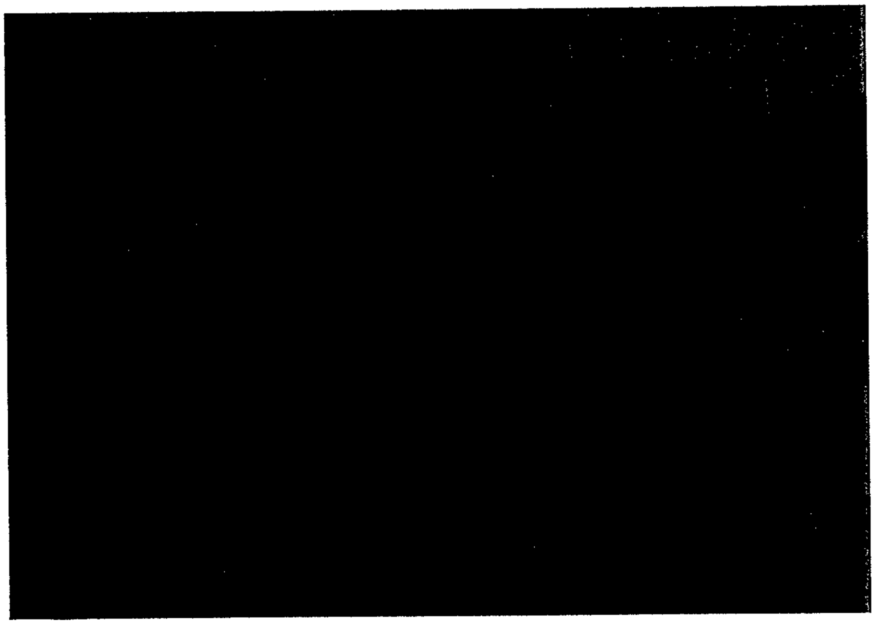

Figure 2: Picture shows an MCNC die which has been pre-released before sputtering nickel on top of it.

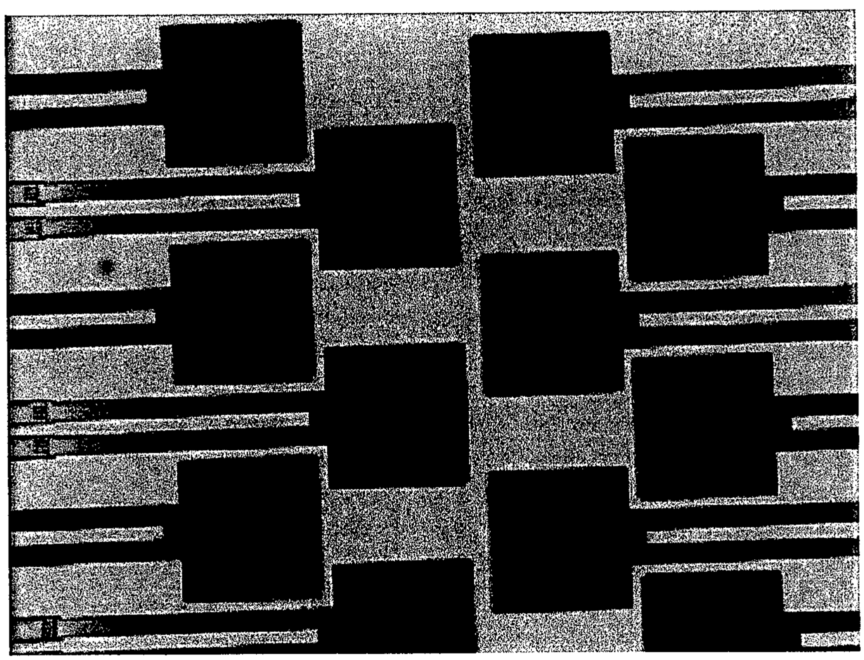

Figure 3: Another picture of a pre-released MCNC die.

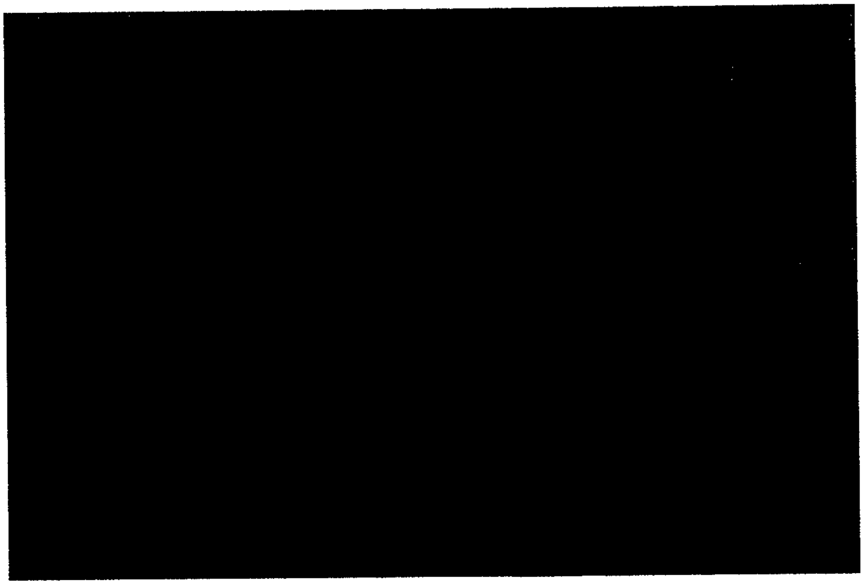

Figure 4: Pre-released MCNC die with sputtered nickel and plated Permalloy on top of it. The thickness of the Permalloy is approx. 0.75 μm.

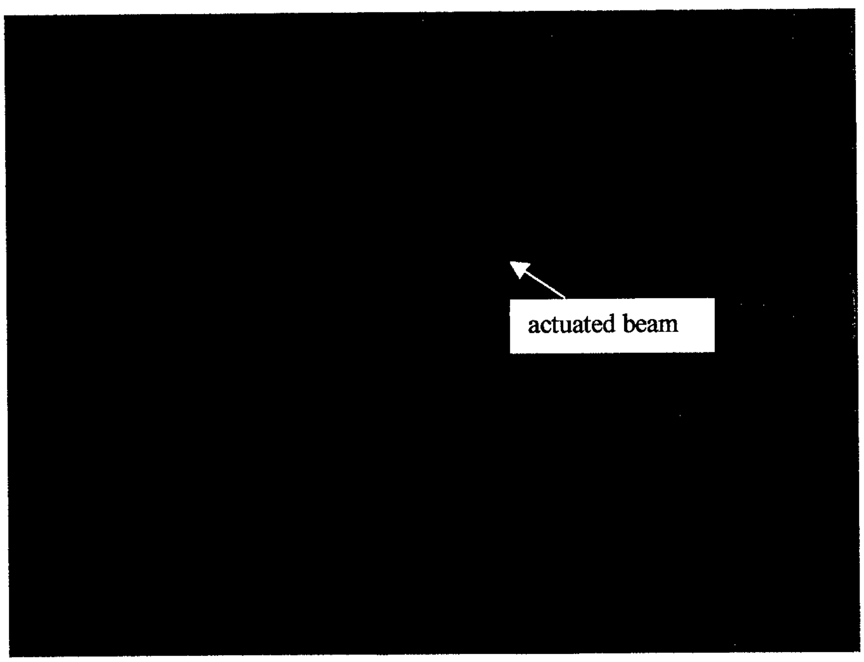


Figure 5: The actuation of the polysilicon beam was accomplished by a small magnet, which was passed at a short distance above the silicon die. In this picture the beam is standing at an angle of 90° with respect to the substrate. Compare this with Figure 4 above.

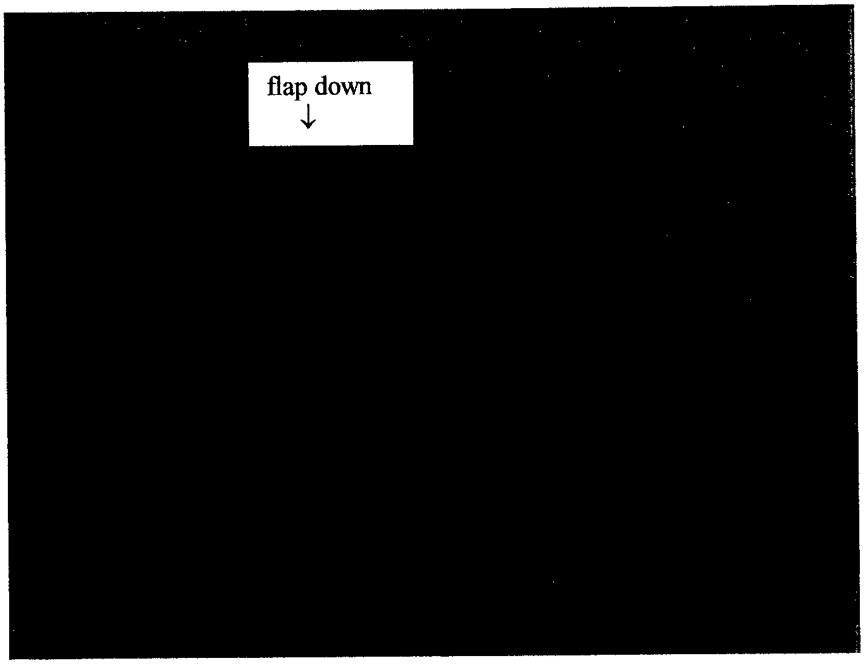


Figure 6: The micro-mirror/flap-like device that can also act like a spacer in the first position lying down flat, parallel to the substrate.

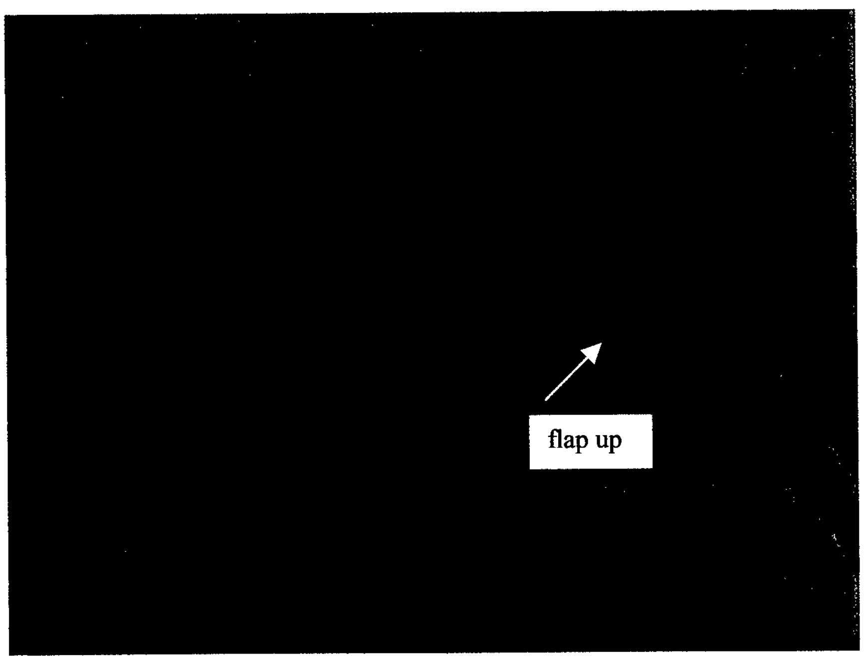


Figure 7: MCNC die with plated Permalloy. The big flap/mirror-like device has been actuated using a permanent magnet beyond 90° with respect to the substrate. Compare with Figure 6 above.

## 5.2 Introduction of SU-8

Although magnetic actuation proved successful, more was needed. In order for the process to be repeatable and reproducible, it was desirable to have dies that were not pre-released because the uniform plating of Permalloy could not be achieved on top of the released slender spacer beams each and every time. Also to maintain electrical insulation between the two glass plates, metal contact should be restricted to certain places of the spacer area as opposed to all over the sample.

New designs of spacer devices were planned. Fabrication of such devices included processes that could either be performed in-house or by a local vendor in order to avoid long MCNC lead time. Thus, spacers made of polysilicon that can be deposited by local vendors were proposed. Furthermore, hinge structures made of SU-8, a thick photoresist material with excellent mechanical properties were also contemplated. The device design and fabrication process sequence were thought through. Masks for fabricating the micro-spacers using the process shown in Figure 8 were prepared.

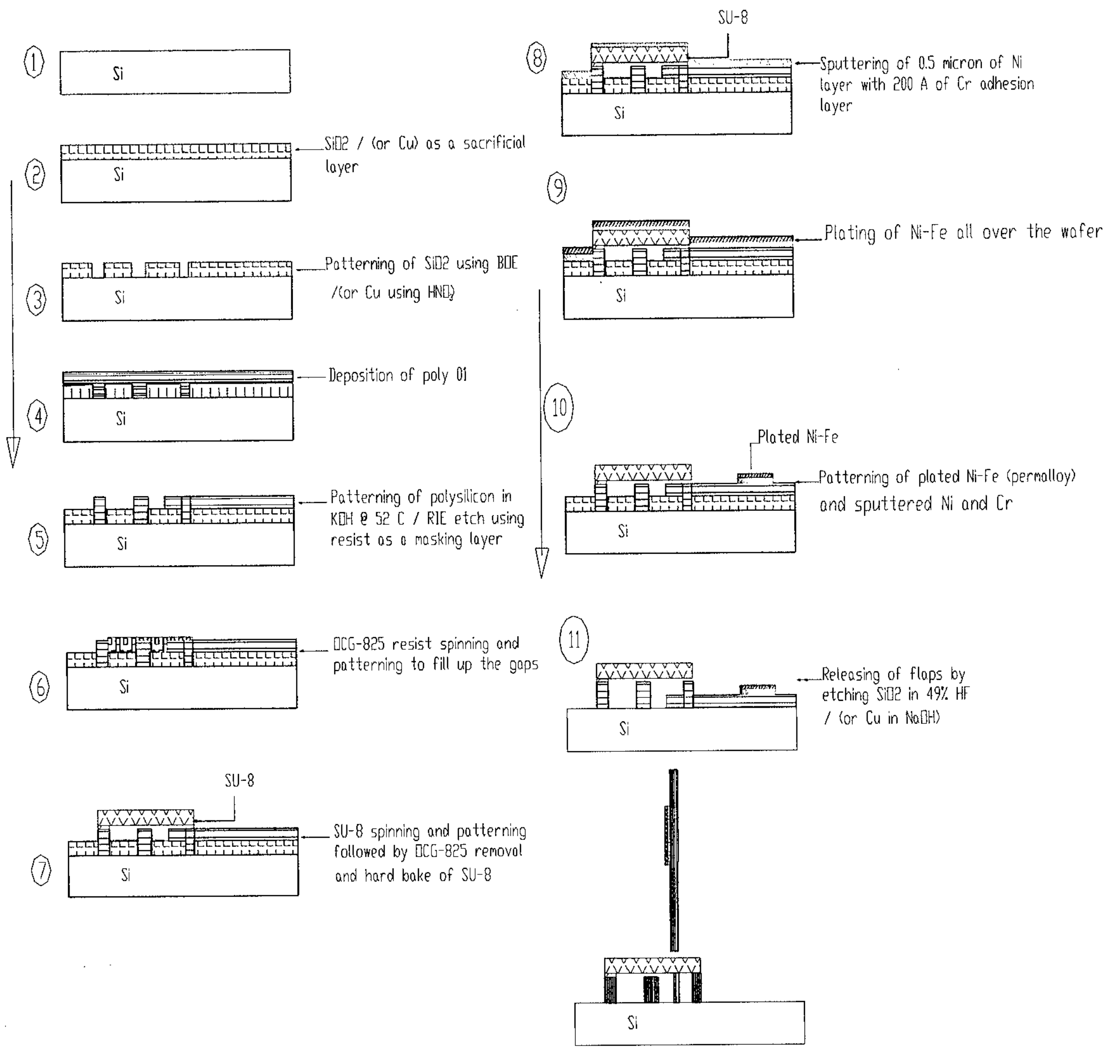


Figure 8: Picture shows the new process flow to fabricate the micro-spacers.

The proposed process steps are outlined below (sequence steps refer to Figure 8.)

A 4'' diameter, 16-mil thick, double-sided polished silicon wafer can be used for processing.

- In step 2, the wafer should be oxidized to grow a layer of silicon oxide approx. 1 μm thick. Once in place, this layer can be used as a sacrificial layer. Since it is difficult to etch oxide using a 50% solution of HF without damaging the metal layers on top, an alternative sacrificial material was proposed. Copper was suggested for the sacrificial layer. It was known to us that polysilicon could be deposited on top of a layer of copper (as specified by our vendor STRATAGLASS) and then be etched away sacrificially using sodium hydroxide (NaOH) solution. However, whether copper could be etched without harming Permalloy remained to be determined.

- In step 3, this sacrificial layer is patterned to make anchors for the polysilicon hinges and to make a spacer mechanism.
- In step 4, the wafer is sent out to STRATAGLASS for the deposition of a 3 μm thick polysilicon layer on top of the sacrificial layer.
- In step 5, gold is deposited on top of polysilicon to act as a masking layer while patterning polysilicon in potassium hydroxide. Alternatively, the wafer can also be reoxidized to create a layer of oxide which could act as a mask for patterning polysilicon.
- In step 6, a layer of OCG-825 photoresist is spun and patterned to fill in the gaps between the anchors of the hinges.
- In step 7, SU-8 photoresist is spun and patterned as shown in Figure 8. SU-8 resist is used in making hinges. After patterning, the whole wafer is heated at 150°C in an oven to harden the SU-8 resist. As can be seen in Figure 8, step 7, SU-8 resist is anchored only at the left-most polysilicon structure. OCG-825 resist prevents the anchoring of the SU-8 resist with the stapled hinges. Once SU-8 resist has been hardened, OCG-825 resist can be removed in acetone.
- In step 8, a layer of nickel 0.5 μm thick is sputtered as a base-plating layer. Chromium is first sputtered below nickel to give it adhesion with the base substrate.
- In step 9, the Permalloy is electroplated on top of the wafer sample, over the entire surface of the wafer.
- In step 10, plated Permalloy is patterned so that the edges of the polysilicon flaps are not bound to the base substrate because of Permalloy plating. Cr and Ni present underneath are also patterned along with Permalloy.
- In step 11 sacrificial layer etching is accomplished with a 50% solution of HF or NaOH.
- Small but strong magnets can be used to raise the spacer beams to stand vertically. SU-8 cantilevers provide the restraining force for holding these spacers in an upright position.

Electronic masks in AutoCAD were made to fabricate the proposed spacer mechanisms. Figures 9 through 13 show various masks intended to be used for fabrication.

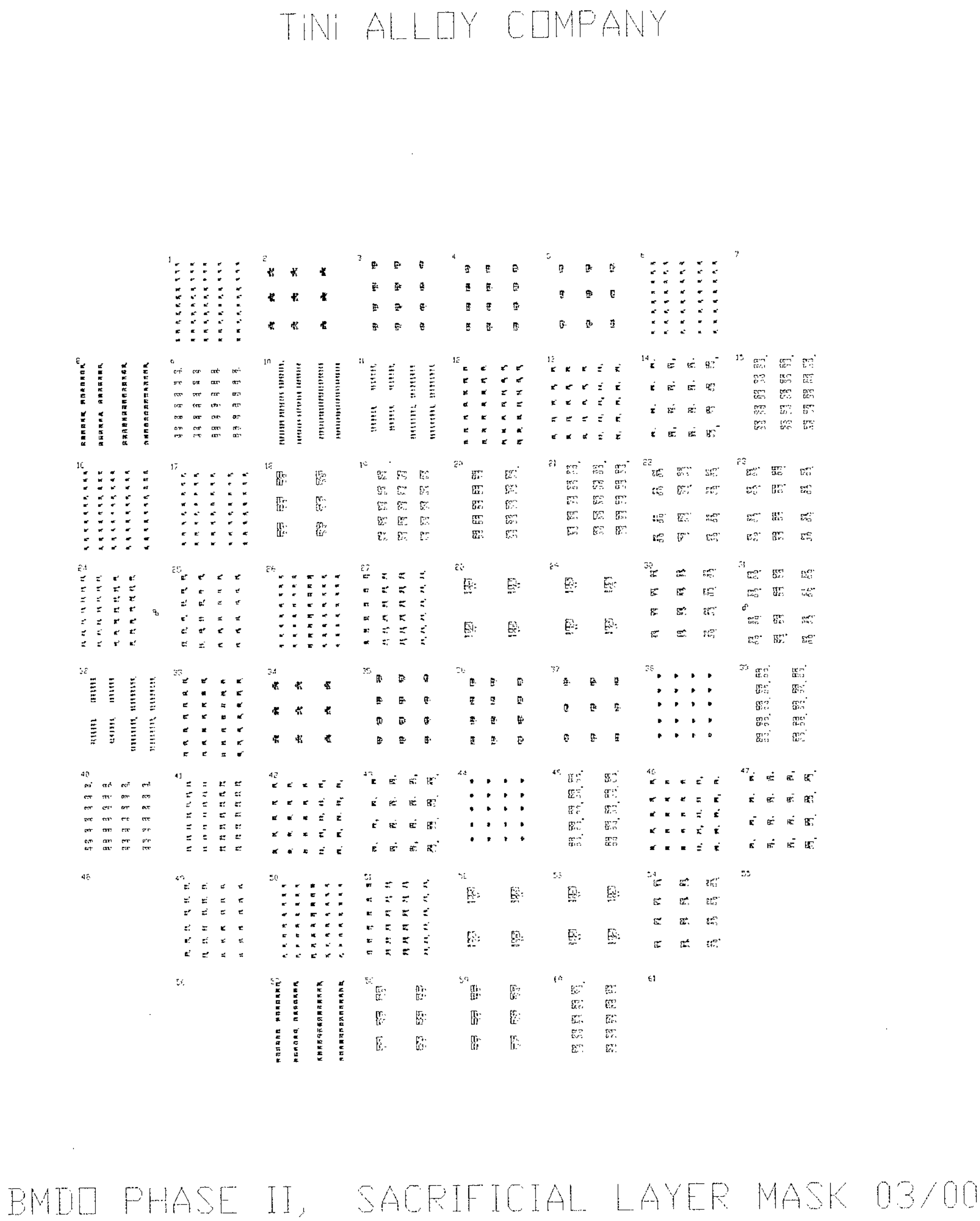


Figure 9: Picture shows sacrificial layer mask to create anchors for the hinge mechanism of the micro spacers.

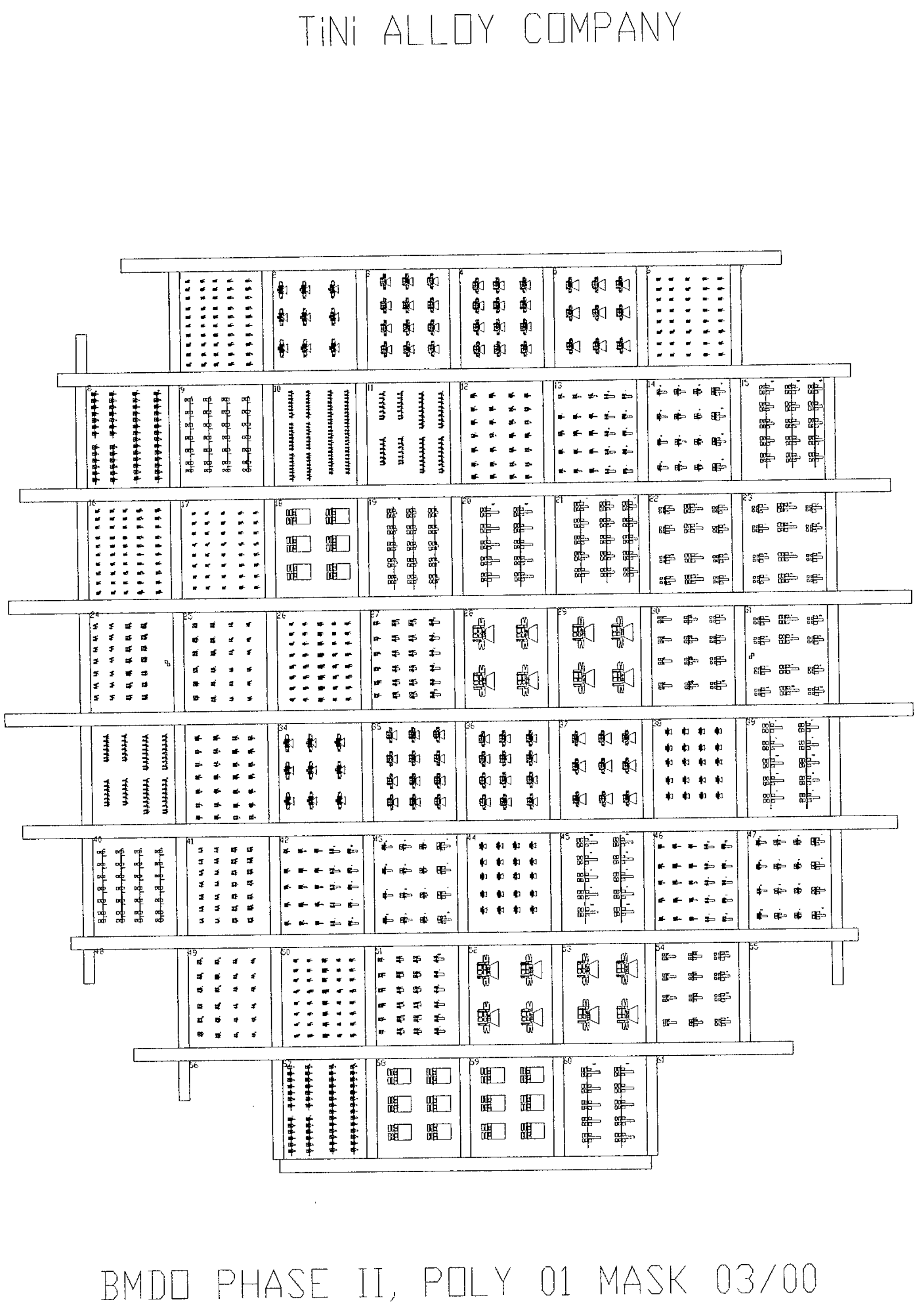


Figure 10: Picture shows a polysilicon layer mask to pattern polysilicon for anchors of the hinges and for fabrication of the spacer mechanism.

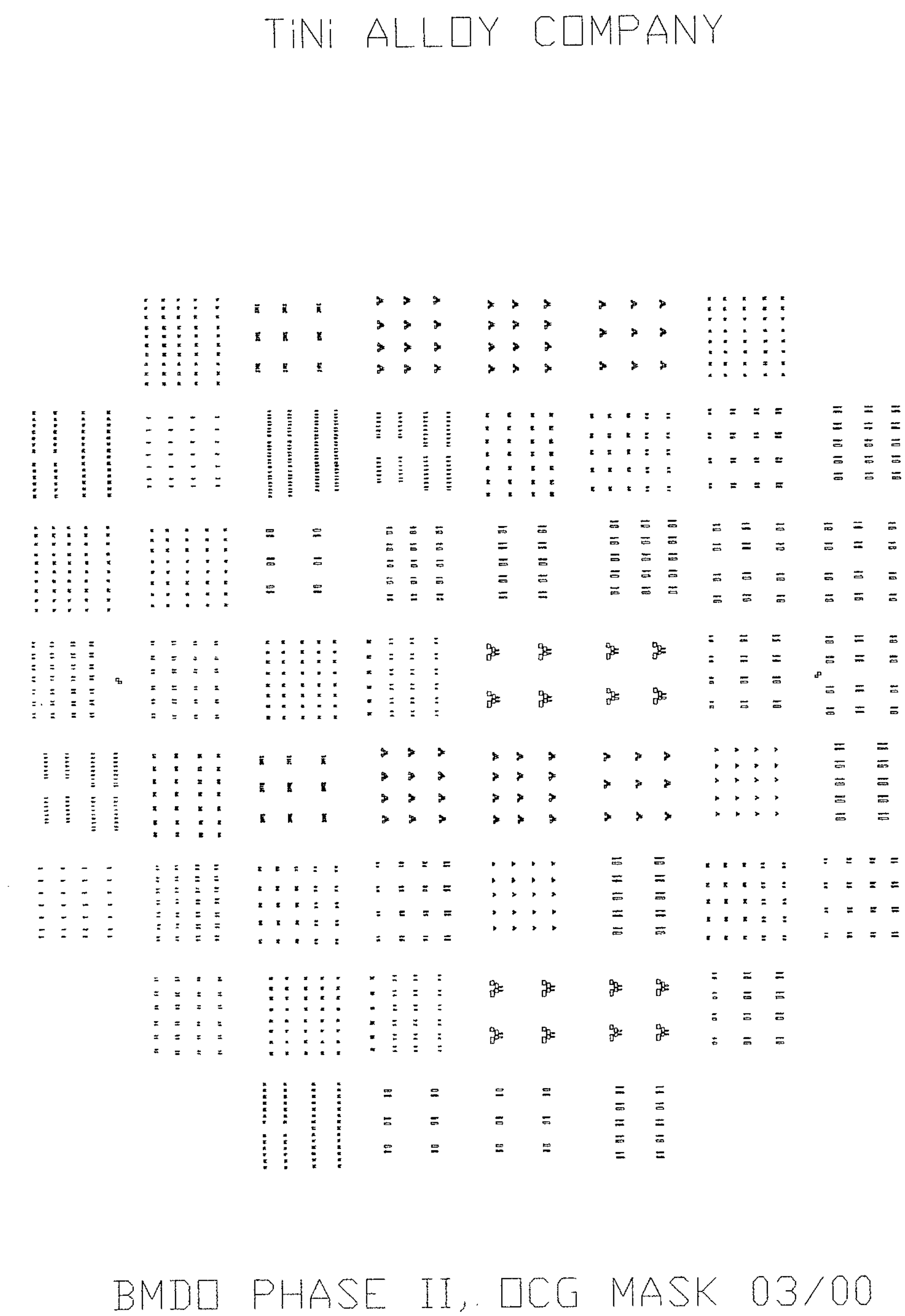


Figure 11: Picture shows OCG layer mask to fill up cavities between spacer and the hinge mechanisms.

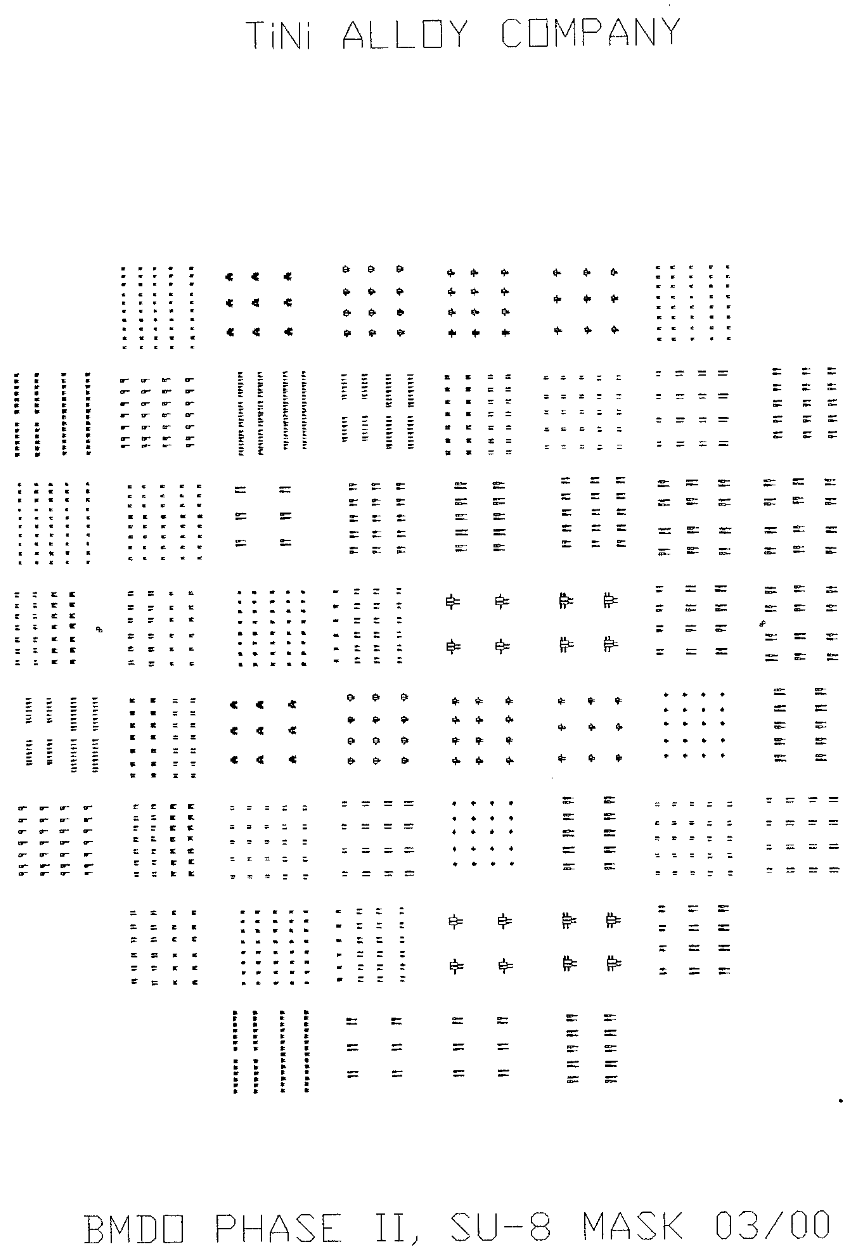


Figure 12: Picture shows mask for patterning the SU-8 layer. This layer is used for holding the polysilicon flaps in the upright position.

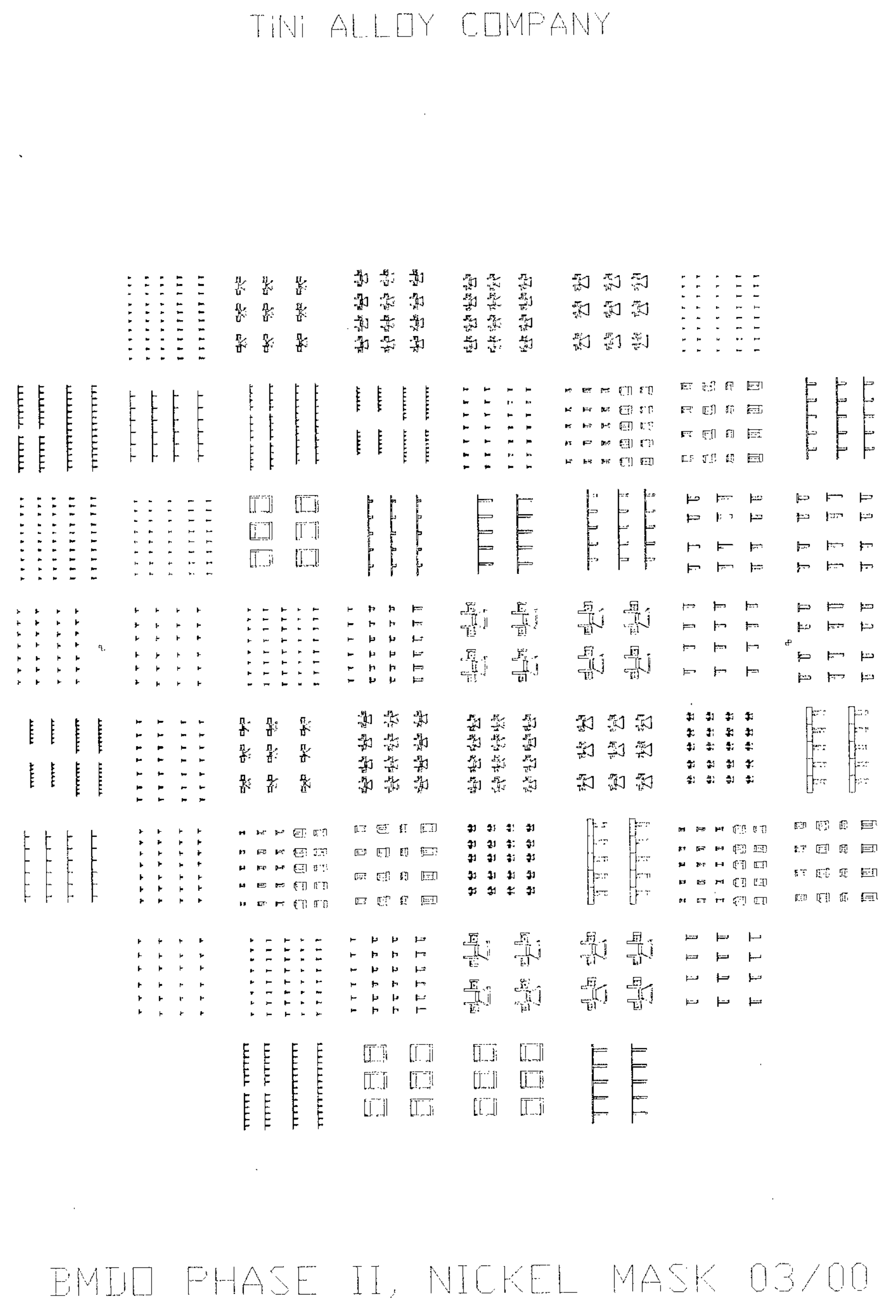


Figure 13: Figure shows the mask for patterning plated layer of Permalloy along with sputtered layers of chrome and nickel.

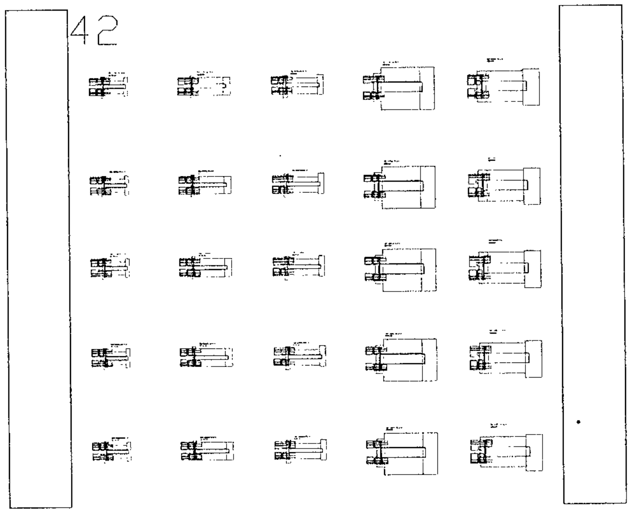


Figure 14: Picture shows all the masks' layers superimposed on one another. Various different sizes of micro-spacers mechanisms are shown.

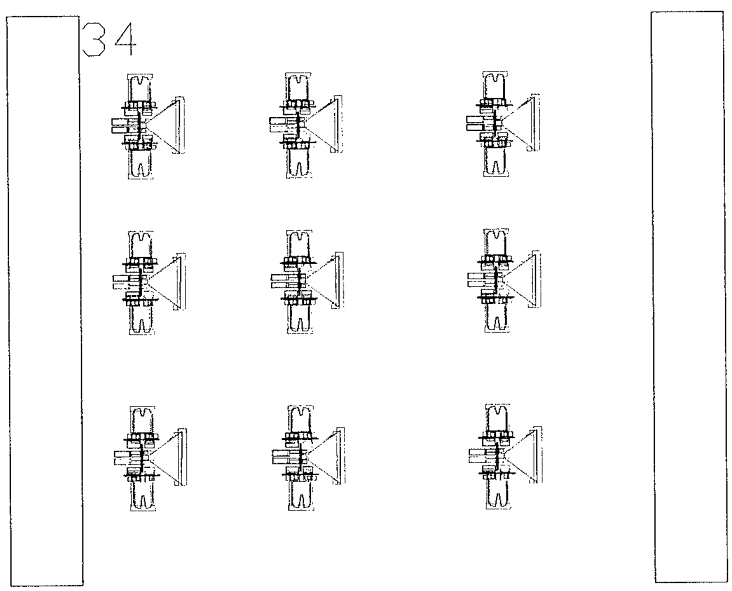


Figure 15: A variation in design of the spacer is shown in this picture. The smaller flaps at the sides are designed to actuate along with the primary flap when they are magnetically actuated. The smaller flaps are designed to lock the primary flaps into a straight vertical position [4]. The size of the die shown is 1 cm x 1 cm.

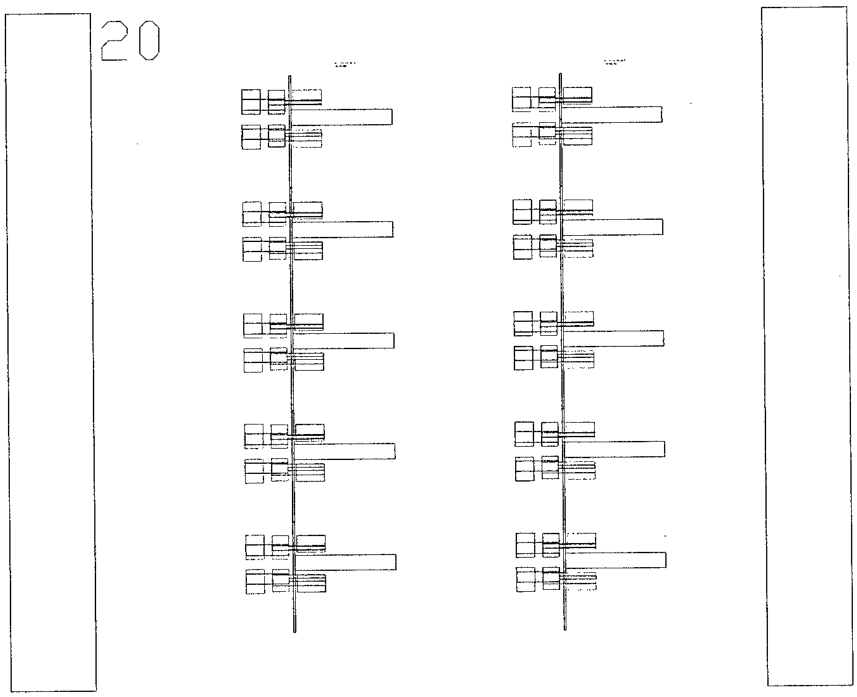


Figure 16: Picture shows the design for an array of polysilicon flaps that are connected to each other. The size of the above cell is 1 cm x 1 cm.

### 5.3 Redefinition of Project Objectives

Although the initial results from the magnetic actuations were promising, further experiments were discontinued for the following reasons:

- Only one time actuation was possible using this technique.
- We still needed to build a reliable latching mechanism in order to lock the position of the spacer once it was raised magnetically to the vertical position.

To avoid the long MCNC delays, it was decided that the latching mechanism, along with the rest of the device, should be built using the in-house facilities. It was our intention, after successfully building the device in-house, to continue with the magnetic actuation for the tilting and the latching of the spacers.

As reported in the fourth quarterly progress report to BMDO (covering the period July 2000 – April 2001 due to special circumstances), some changes were made to the final objectives of the

Phase II research work. In the report, Dr. David Johnson wrote:

*"The work reported here is on-going research and development of MEMS devices, especially out-of-plane structures that are fabricated on the surface of plane substrates and erected to vertical position by shape memory thin film microactuators. These structures have several significant applications, including spacers for field effect displays, optical switches, and micro-optical benches[5]. The basic concepts were developed in Phase I, reported in January 1998. Phase II was funded in 1999 with the requirement that after the first $100K was spent, the remaining funds would be released only if matching funds were found. Approximately $40K was spent by June 2000. The work carried out was reported in three Quarterly Progress Reports covering the period from October 1999 through June 2000. Further work was postponed because there were at that time no prospects for matching funds.*

*Since April 2000, TiNi Alloy Company has been engaged in development of fiber optics switch components, funded in part by a commercial entity: OPTIMEMS Inc. It has become increasingly apparent that the technology originally envisioned for use in spacers for FEDs is applicable to making cross-point switches for fiber optics. Similar hinged structures, originally developed by Chris Pister at the University of California, and improved upon by several other researchers, are used in at least two of the fiber optic switch designs that rely on electrostatic actuation [6],[7],[8]. It is clear that shape-memory actuation is better suited to this application because the actuator can be made much smaller. The management of OPTIMEMS is sufficiently confident of the applicability of this technology that they have agreed to match funds for continuation of Phase II R&D contingent on successful actuation of out-of-plane devices by means of shape memory thin film microactuators. We are resuming work with a goal of demonstrating feasibility of rotating hinged micromirrors to a vertical position relative to the substrate and latching them in place. When the agreed $100K is exhausted (anticipated date: July 2001), we will submit the results and a commitment for continued matching funds."*

It should be noted that Optimems has subsequently not continued operations because of the turn-down in fiber optics deployment beginning in the third quarter of the year 2000. TiNi Alloy Company did not receive the funding referred to above. We continue to seek funding for Optimems and hope to be reimbursed the substantial development costs expended by TiNi Alloy Company to date.

## 5.4 Description of Device Design and Plan for Continuation of Work

The methodology used eliminates the most critical problem encountered in Phase I, namely step coverage of sputtered TiNi film at the edge of the mirror. Instead, composite bending beams of silicon and TiNi film are being used to provide actuation and latching [9]. The design closely follows that proposed in 1999.

Figure 17 shows a layout of one configuration. All components, mirror, hinges, and actuators, are fabricated by MEMS processes. Figure 18 shows an elevation view of the hinge-actuator combination illustrating how it is lifted to a vertical position and returned to a horizontal position.

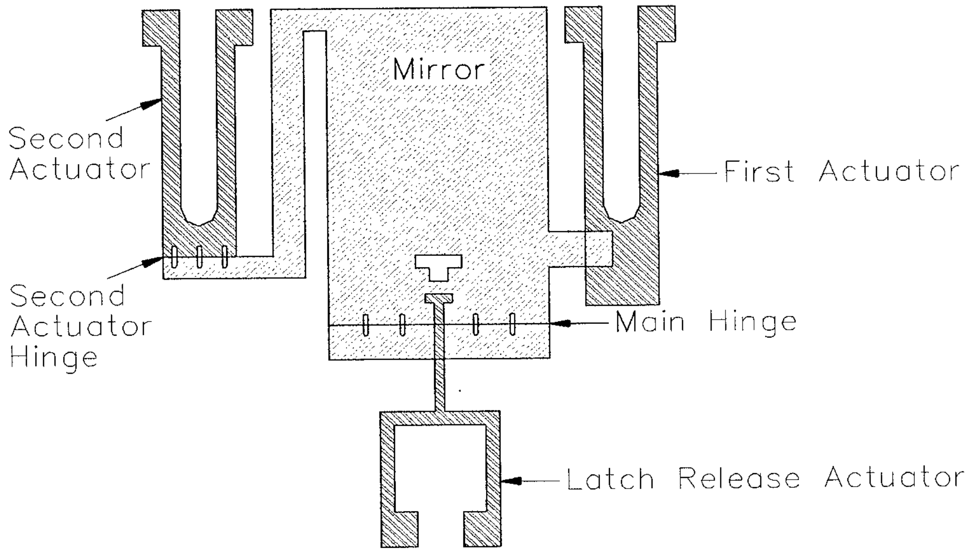


Figure 17: Proposed configuration of bending-beam actuators and hinged structure.

The first actuator lifts the mirror to a vertical position, a second latches it in place. A third actuator is used as a release mechanism so that the plane mirror may be returned to its original horizontal position.

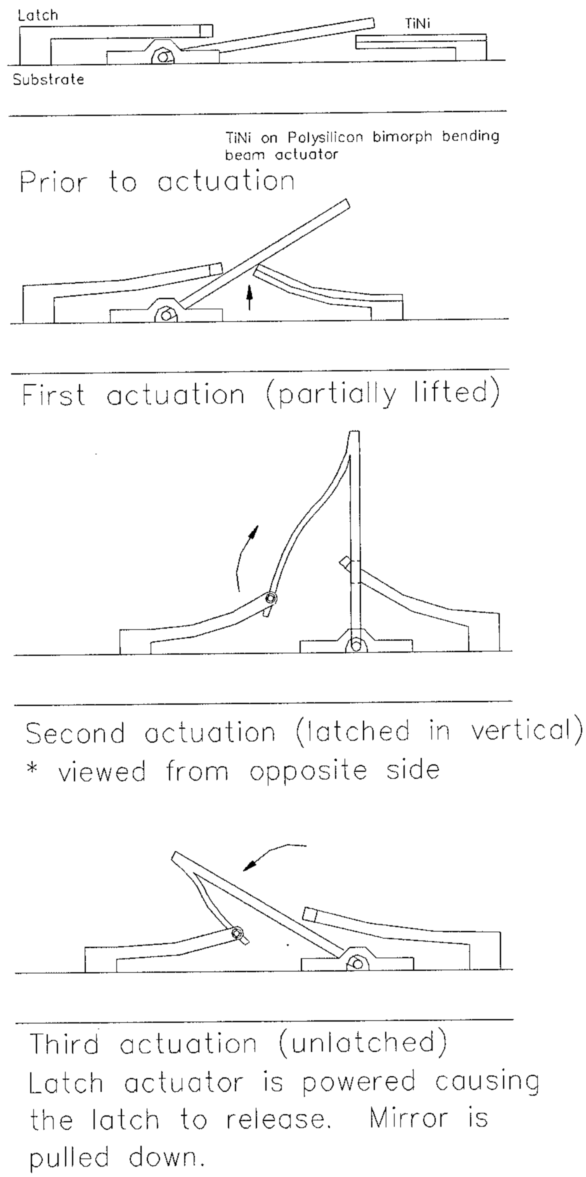


Figure 18: Illustration of how the actuator, hinge, and latch combination work together.

A complex beam will be designed to carry actuation to 90 degrees. A latching mechanism is necessary to secure the mirror in a vertical orientation. A composite beam will be incorporated to enable the device to be unlatched by a TiNi actuator.

With limited time and funding in hand, it was necessary to choose materials and fabrication processes that were readily available in-house. A novel approach for making the mirror/hinge structure was proposed. Use of a silicon-on-insulator (SOI) wafer to make the mirror was proposed. The excellent mechanical properties and extremely polished surface of silicon wafers are ideally suitable for mirror structures. A thick negative photoresist, SU-8, was proposed to make hinges. Hardened SU-8 has been reported to have excellent mechanical properties and has been used to make mechanical parts in MEMS. A thick layer of OCG 825 was proposed to be used between SU-8 hinges and mirror pins which could later be dissolved in standard solvent in order to release the SU-8 hinges. TiNi film sputtered onto the top surface would be patterned to make the actuators.

Several project meetings were held at TiNi Alloy Company to discuss the design and fabrication of the proposed device. Present were:

David Johnson
Vikas Gupta
Valery Martynov

Initial device designs and process sequences for fabrication of the device were laid out. Some possible problems in fabricating the device were anticipated:

- After etching deep cavities in the back side of the SOI wafer, the front side membrane layer may be too thin and fragile to continue with further processing.
- Etching of mirror structures in the front side will cause trenches and cavities in the wafer surface and may cause nonuniformity problems in photolithography. A nonuniform surface can cause nonuniform coating of photoresist which as a result causes nonuniform patterning of photoresist.
- The idea of using OCG 825 photoresist to fill between the SU-8 hinge structures and mirror pin structure was characterized as feasible but experimental.
- Compatibility between the chemicals and processes for OCG 825 and SU-8 was to be determined.
- The process of dissolving the thick layer of OCG 825 after the baking of SU-8 structures needed to be refined with some experiments.
- Selection of chemicals to release the final device without damaging TiNi or SU-8 structures was to be done based on experiments.

The advantages of using SU-8 photoresist and SOI wafer were recognized as being:

- SOI wafers provide a uniform, thin layer of silicon which is not only suitable for making mirror and actuator structures, but also can be released from the base surface by etching away the oxide layer from underneath.

- A mirror structure made from silicon is extremely flat and has a polished surface suitable for optical applications.

- The proposed design completely eliminates the problem of step coverage of TiNi over mirror structures.

- SU-8 photoresist has excellent mechanical properties for the fabrication of strong hinges and other mechanical structures[10].

- Process requirements for TiNi are compatible with other processes.

- All the proposed materials can be deposited and processed using in-house facilities.

Due to the complexity of the device and limited remaining funding and time, the working group arrived at a consensus that the goals for the remainder of the Phase II project should be:

- Design and fabricate mirror and hinge structures using SOI wafer and SU-8 photoresist.

- Release mirror and hinge structures.

- Tilt the mirrors from horizontal position to vertical position.

- Record the images of tilting of mirrors.

Once the fabrication and function of mirror and hinge structures have been proven successfully, these same designs can be used, modified only to include a latch mechanism to secure the mirrors in vertical position.

## 5.5 Fabrication of Out-Of-Plane Structures Based on SOI Wafer and SU-8 Photoresist

Polysilicon to build mirror and hinge structures in out-of-plane devices has not been suitable because of the following limitations:

1) Polysilicon can only be deposited by outside vendors and they have long lead times resulting in severe delays in getting the devices back, and

2) The maximum possible thickness of a polysilicon layer is quite low, limiting device design flexibility.

A novel approach of making mirror and hinge structures using SOI wafer and SU-8 was proposed. An SOI wafer is comprised of three layers: a silicon handle layer about 400 $\mu$m thick, a silicon oxide layer 1.5 $\mu$m thick, and a silicon membrane layer 15 $\mu$m thick, as shown in Figure 19.

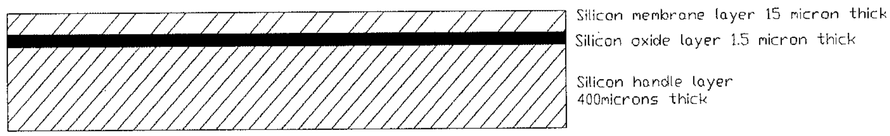


Figure 19: Cross-sectional view of an silicon-on-insulator (SOI) wafer.

In our device design, a handle layer was used for creating deep cavities by silicon etching. The silicon oxide layer works as a stop etch layer preventing over-etching of silicon. Mirrors and actuator structures were fabricated from the top Si membrane layer. SU-8 was deposited on top of the membrane layer and patterned [10] to make hinges for mirror structures. TiNi thin film was sputter deposited on the silicon beam structures (also made from the membrane layer). A composite bending beam of silicon and TiNi thin film is intended to be used as actuator to raise mirrors. Once fabricated, the mirror, hinge and actuators in the membrane layer were released selectively by etching away the oxide layer underneath. A drawing of a conceptual device design is shown in Figure 19. This methodology eliminates the two most critical problems encountered in Phase I: 1) step coverage of TiNi film during sputter deposition, and 2) dependency on MCNC foundry and/or local vendors for polysilicon processing.

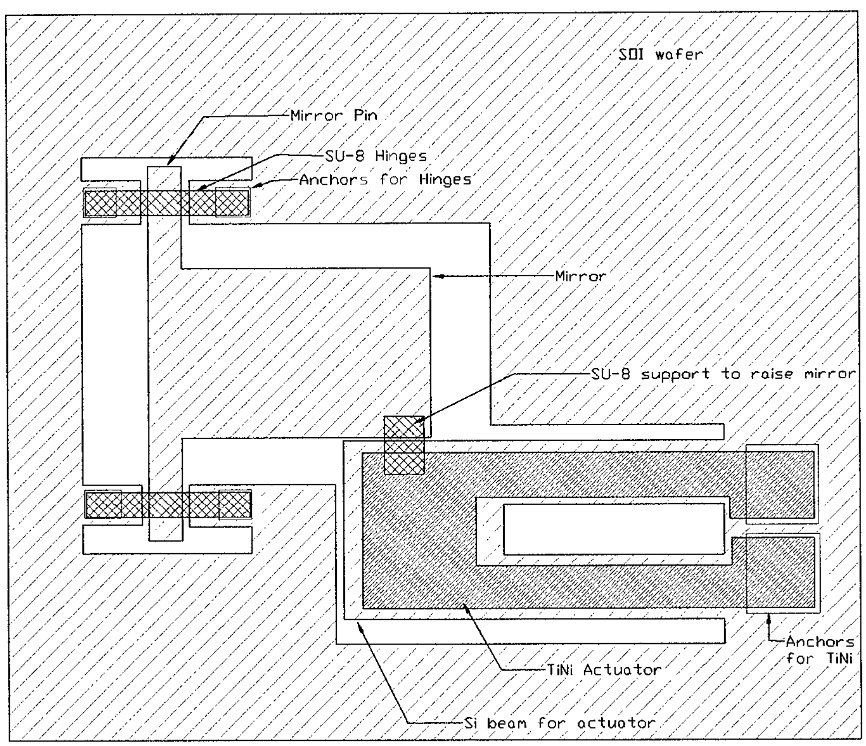


Figure 20: Top view of proposed device layout.

Process sequence for the fabrication of the proposed device is shown in Figure 21.

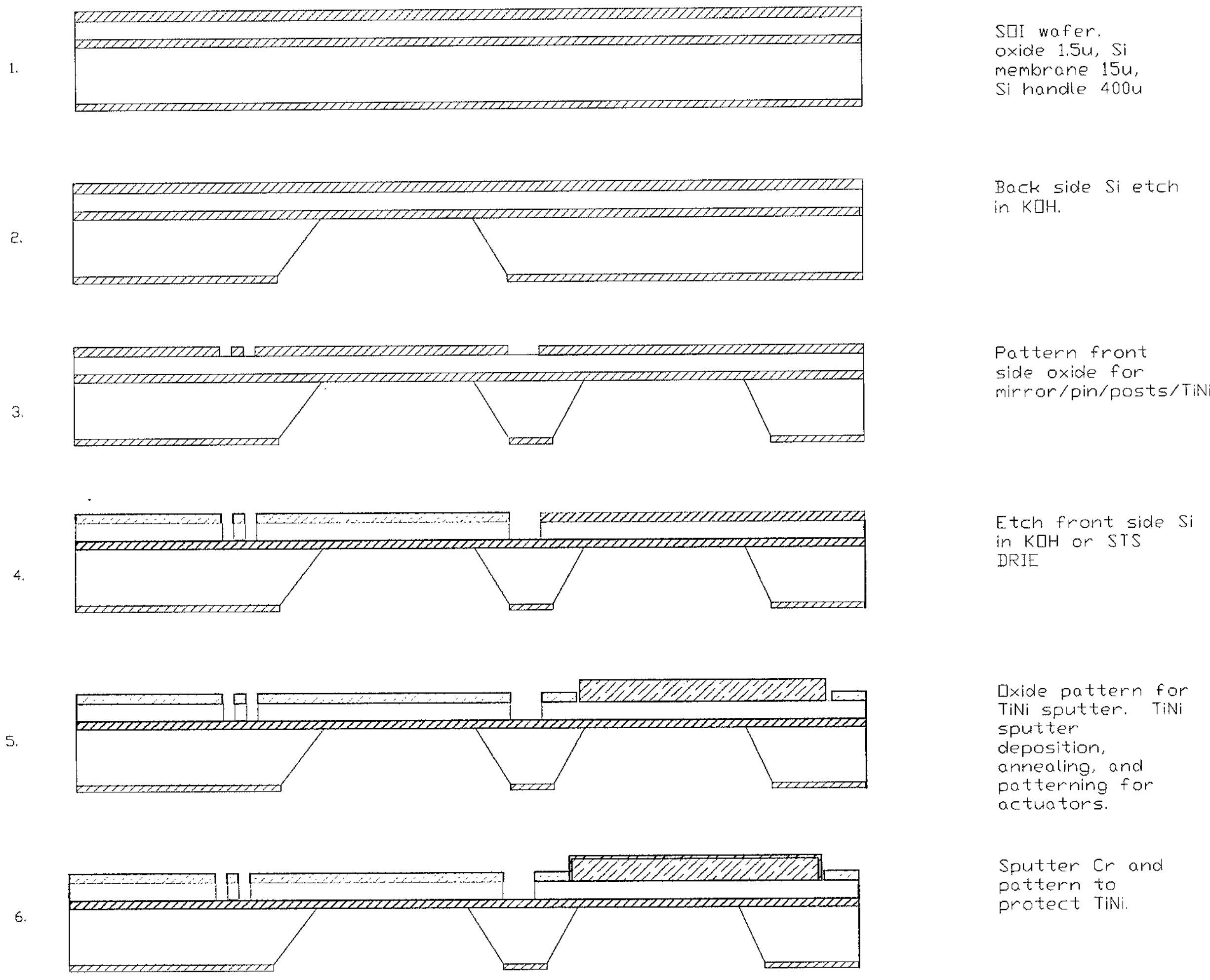


Figure 21: (continued on page following)

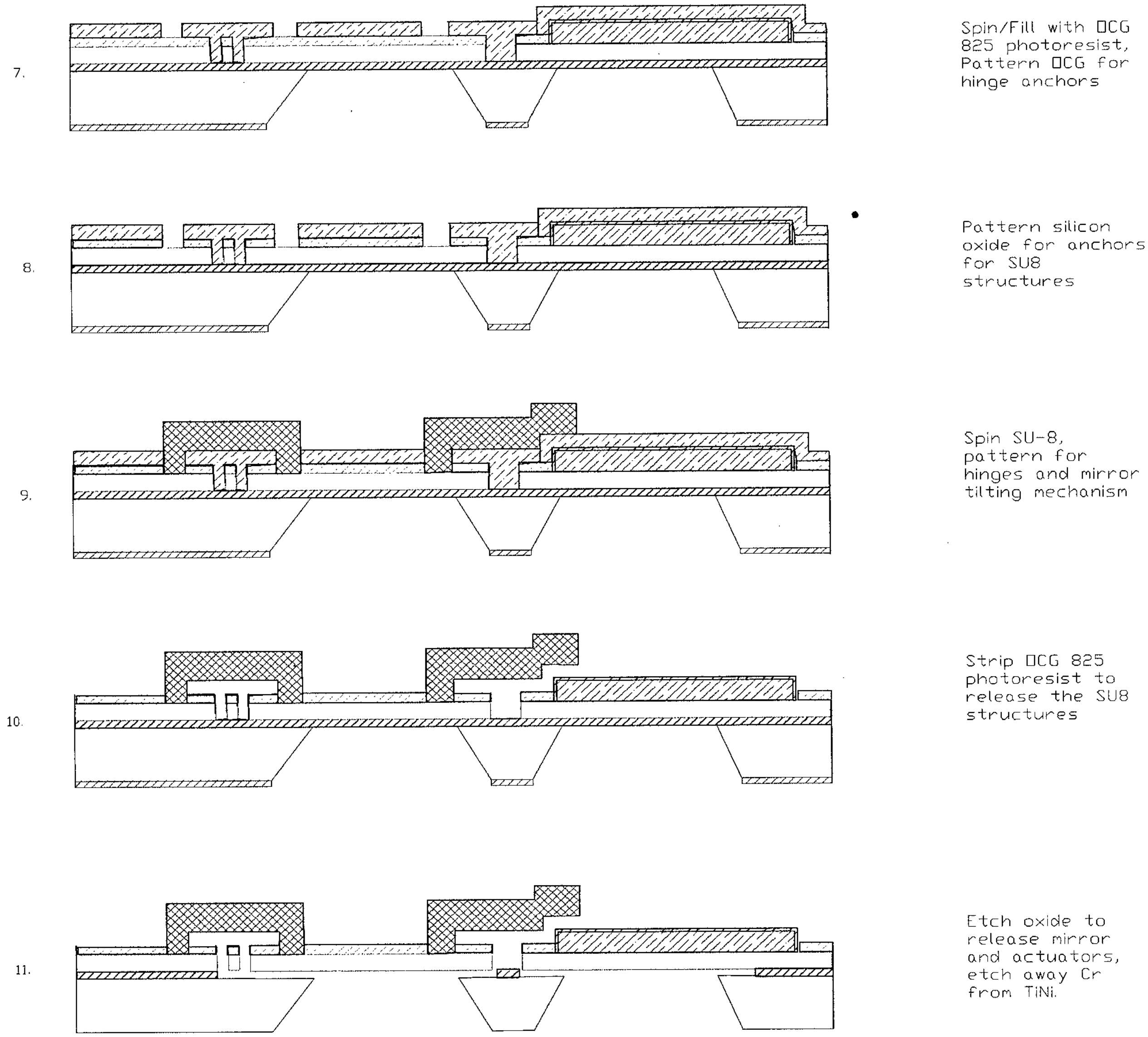


Figure 21: Processing sequence for fabrication of device.

According to our proposed Phase II goals, we decided to make photomasks that contained the following variations in device designs:

- Different sizes of mirror structures
- Different lengths of movable pin structures
- Different sizes of SU-8 hinge structures
- Designs for silicon etch performed using wet etching and dry etching (both computer versions of masks for each layer were made in AutoCAD 2000)

Figures 22 - 25 illustrate all the mask designs used in fabricating the device. These AutoCAD designs were sent to a mask vendor (Infinite Graphics Incorporated) to make photomasks with well-defined clear and dark regions. Due precautions were taken to ensure that clear and dark regions in masks were defined properly for both positive and negative photoresist. All photomasks, except the one for "mirror", were printed on plastic films (called "emulsion on film") with 8000 dpi printers. The "mirror" mask has the smallest features (15 μm) and therefore a specialized high resolution printer called LASERWRITE was used to print this mask. Mask films were then cut to fit on a 5" transparent glass plate and attached using scotch tape for use on a photoaligner during the ultra violet exposure.

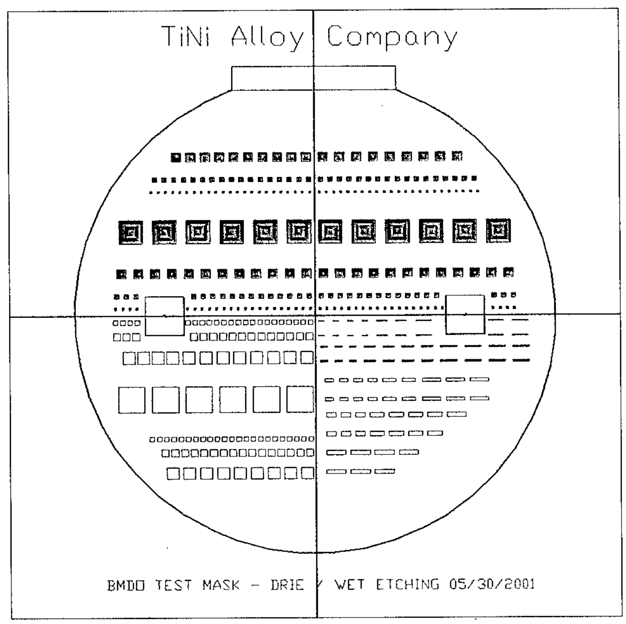


Figure 22: Mask layout for back etch designs.

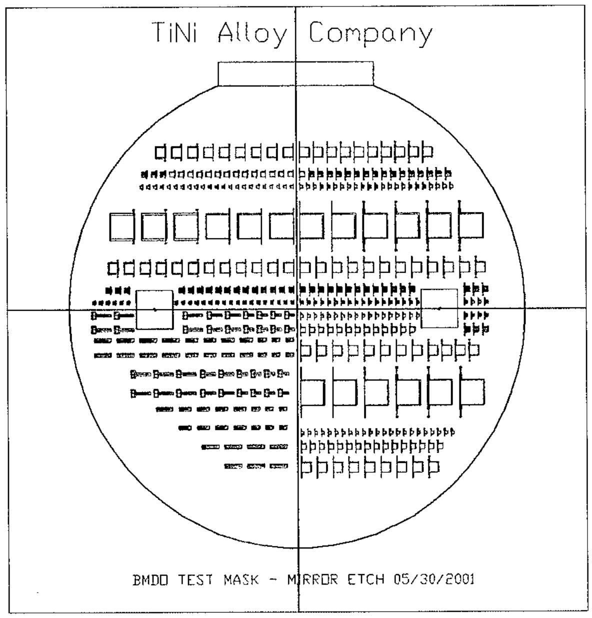


Figure 23: Mask layout for mirror and actuators front side etch design.

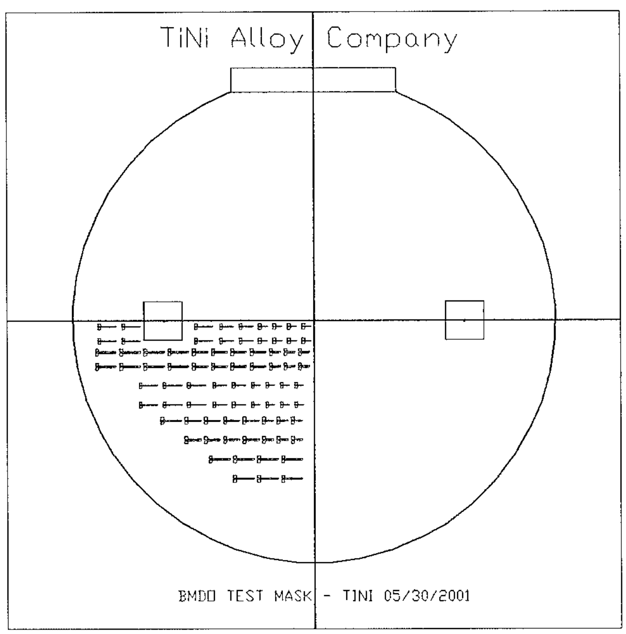


Figure 24: Mask layout for TiNi thin film design.

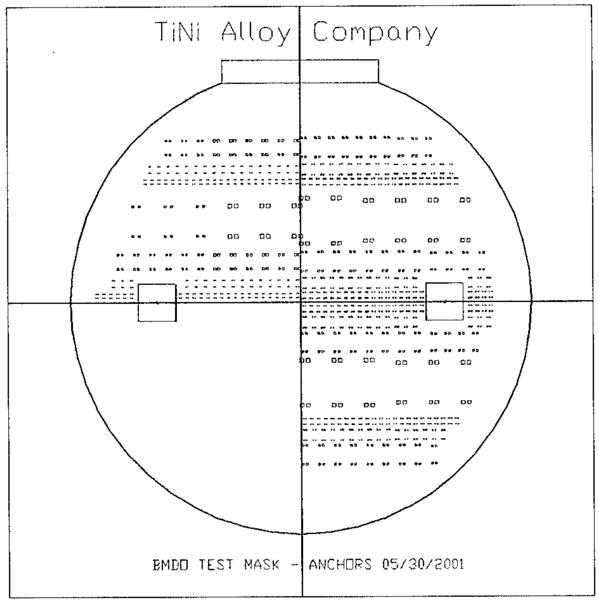


Figure 25: Mask layout for making anchors for SU-8 structures.

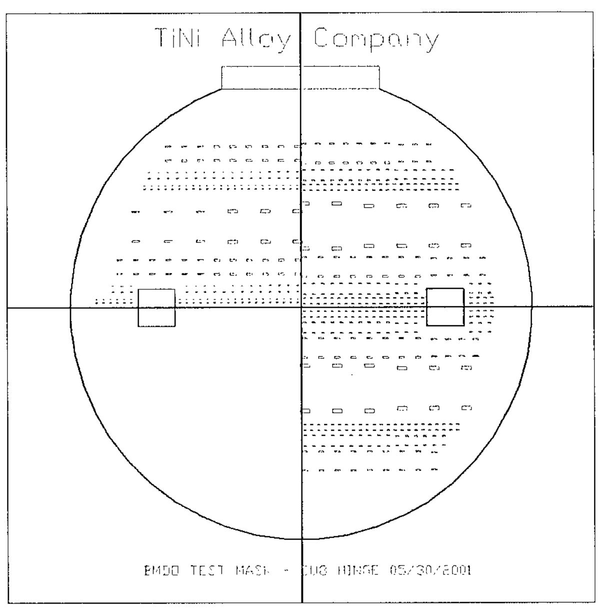


Figure 26: Mask layout for SU-8 structures.

## 5.6 Fabrication of Mirrors and Actuators

Four inch diameter SOI wafers were oxidized (using a wet oxidation process) to obtain approx. 1.0 μm thick silicon oxide layers on both sides of the wafer. Photolithographically, alignment marks were then produced on both sides of the wafers. Wafers were then again oxidized on both sides. A thin layer of OCG 825 photoresist was applied on the back side of the wafer and patterned to form deep cavities in silicon. Front side oxide was protected by an OCG 825 layer during back side oxide patterning. Deep cavities in silicon were etched in a KOH 20% solution bath at 50°C. Typically the etch rate of silicon in KOH 20% at 50°C is about 10 μm per hour. The buried oxide layer in the SOI wafer works as an etch stop layer resulting in deep cavities with uniform depth across the wafer. Deep cavities in the back side of the wafer leave a thin (15 μm) membrane silicon layer on the front side which needs to be protected from breaking in subsequent processes. This was achieved by attaching the back side of the processed wafer to a plain silicon wafer by means of a thin layer of OCG 825 photoresist. After baking the photoresist at 90°C, the sandwiched layer photoresist worked as a glue to hold the two wafers together and thus provided a strong base substrate for membrane structures. The bonded wafers can be separated easily by dissolving the photoresist in a solvent like acetone or EMT. This process of bonding and delaminating of wafers was performed several times in this project. Alternatively, blue tape was also used experimentally as a support layer but failed because of following reasons:

- Although blue tape provided a support for a fragile wafer on a vacuum chuck, there was still a reasonable amount of warp in the thin membrane section of the silicon layer.

- Wafer with blue tape on the back side adheres strongly to the vacuum chuck posing a threat of breakage when the wafer is forced loose from chuck.

- Blue tape, after being removed from the chuck, usually has an uneven surface at the bottom (a replica of groves in vacuum chuck.)

- The uneven bottom surface of blue tape sometimes causes a nonuniform alignment of the wafer in the photo-aligner.

The front side of the SOI wafer was patterned for mirror and actuator structures using OCG 825. OCG 825 was first spread at 90 rpm for 5 secs and then ramped up to 4000 rpm for 30 secs. After baking the photoresist at 90°C for 30 mins, it was aligned against a mask in a photoaligner and finally exposed with UV for 20 secs. UV exposure causes cross linking in photoresist. After developing the photoresist, it is baked in a clean oven at 120°C for 30 mins. After baking at 120°C, patterned photoresist is strong enough to be placed in harsh solutions (except solvents) without damaging it. Silicon was etched in KOH 20% solution at 50°C. Etching of silicon stops in KOH once the oxide layer is exposed. Figure 27 shows a patterned mirror structure. In wet etching of silicon, typically, convex corners of a structure etch in a lateral direction as can be seen in the Figure 27. Because of this corner etching, if the mirrors are over-etched in KOH, the length of the pins will shrink drastically in size. One method to overcome this problem is by introducing corner compensation features in the design. Small square holes on the mirror are to accelerate the final release process.

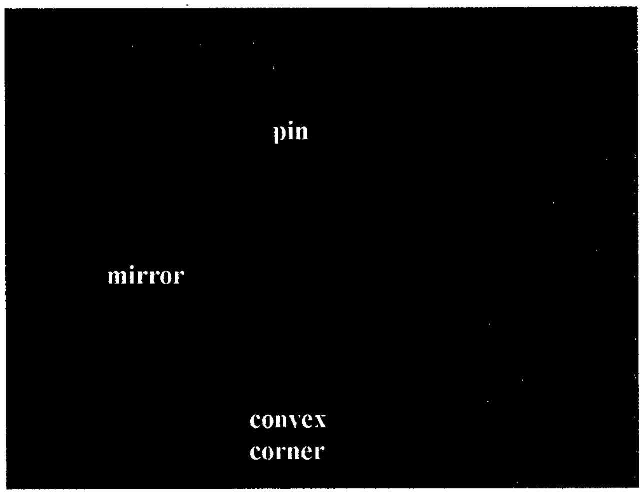


Figure 27: Photo of an etched mirror structure (one half) on SOI wafer.

After the KOH etching process, to improve the adhesion of the photoresist, the wafer surface was cleaned by a sputter-etch technique. The wafer was sputter-etched at 500 Watts RF power for 10 mins at 2 mtorr argon pressure in a Perkin Elmer PE4400 system. Wafers were rotated during the sputter-etch process.

To form actuators on the wafer, about 3 μm thick TiNi film was sputter deposited on the wafer in a Perkin Elmer PE4400 system. The film was sputtered at 2 kWatts DC power at 2 mTorr argon pressure (system base pressure = 2x10-7 Torr). To crystallize the TiNi material, the film was annealed at 500°C at a low 10-6 torr vacuum. TiNi film was then patterned using OCG 825 photoresist to create TiNi actuators. Due to the nonuniformity of chemical composition of the TiNi film across the wafer, a partial delamination of the film was seen at the outside edge of the wafer. However, the film adhered well over much of the wafer.

The SOI wafer was bonded to a plain wafer to act as support for the subsequent processes. TiNi thin film was patterned using the photoresist and the "TiNi" photomask. As expected we found that the thickness of the photoresist wasn't uniform across the wafer due to the uneven silicon surface (etched trenches). However, by increasing the UV exposure time, we were able to pattern the photoresist with reasonable uniformity. The high magnification inspection showed that the photoresist was well patterned. The alignment of the wafer with the mask was good. The photoresist was heated to 120°C after the development process to make it more resistant to chemicals other than solvents. TiNi thin film was successfully etched in our usual etchant:

1 part buffered oxide etch (BOE): 12 parts nitric acid ($HNO_3$): 13 parts water ($H_2O$).

The etch rate of the film was found to be approximately 3 μm per minute. Because of some undercutting of the photoresist, the width of the patterned TiNi actuators were reduced. The effect of the undercutting was more severe on the thin TiNi actuators. TiNi bands that were 20 μm wide or less were affected more severely than the wider ones. Figure 28 shows the rough edges of an etched TiNi film.

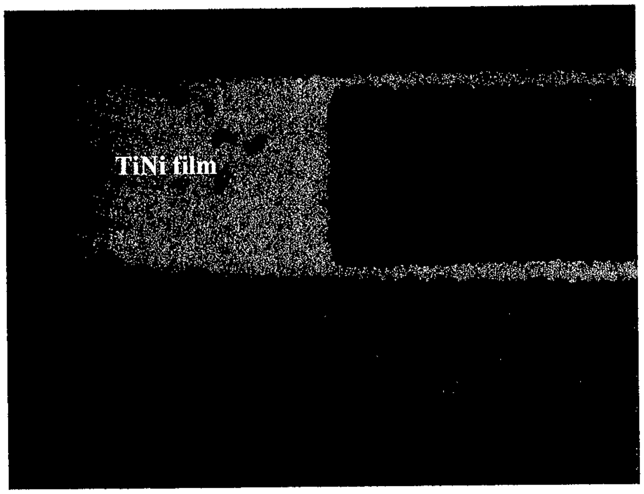


Figure 28: Patterned TiNi film on an etched silicon beam.

To protect the TiNi film from the subsequent process of final release in BOE/HF solution, it was necessary to cover the film with a protective chromium layer. A chromium layer of approx. 1000 angstrom thick was sputter deposited on the wafer in the PE 4400 system. The chromium film was sputtered at 500 Watts RF power at 2 mtorr argon pressure (base pressure = low 10-7 torr) for 30 mins while the wafer was being rotated under the chromium target. The chromium film was etched in a standard chromium etchant to create patterns for the protection of the TiNi actuators.

The next step was to prepare the anchors for the hinge structures. Since silicon oxide was chosen as the sacrificial layer for the final release of the devices, there was no other choice except to use the silicon surface as the anchors – that required another repetition of photolithographic steps for the patterning of the silicon oxide layer. Again, in order to protect the thin and delicate mirror structures, the wafer was bonded on to a support silicon wafer. The OCG 825 photoresist was spin coated, UV exposed, developed and hard baked. The anchors were made by etching away the silicon oxide in buffered oxide etchant (BOE). The wafer was placed in EMT at 80°C to strip the photoresist from the top surface of SOI wafer, and to delaminate the back support wafer from the back. The EMT solution was replaced with a fresh solution from time to time in order to get the best cleaning results. Extreme precautions were taken during the transfer, cleaning, rinsing, and drying of the wafer to avoid breaking the delicate structures.

After the above procedures, the next step was to deposit a thick layer of the OCG 825 photoresist on the wafer which acts as a sacrificial layer in releasing the hinge structures. From Figure 29, it can be seen that coverage of the photoresist coating must be good in order to obtain a good quality hinge structure. It was critical to achieve a sufficiently thick coating of photoresist so as to not only fill the trenches but also produce a spacing layer between the pin and the hinge structure. This gap determined the clearance between the hinge and the mirror needed to rotate the mirror inside the hinge.

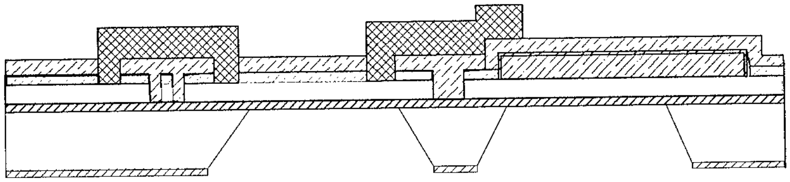


Figure 29: Diagram shows the coverage of the photoresist under the SU-8 hinge.

Several experiments were carried out to determine the optimum photoresist thickness. The following elements in photoresist coating were varied: spin rates, spin times, and number of coatings. First, the photoresist was spun at 90 rpm for 30 secs and was coated three times. The photoresist was baked at 90°C for 45 mins after each spin. After the end of the third spin, a large number of cracks started to propagate in the photoresist due to the multiple baking cycles. To eliminate these cracks, the number of photoresist coatings were reduced to two but the spin rates and spin times were kept the same as previously. In this case we found that, though the photoresist surface was flat and smooth, the process caused large solvent bubbles to form between the photoresist and the SU-8 layer deposited in the subsequent process. Sometimes, these large bubbles were big enough to cover a large part of the anchors which would ultimately yield a poor quality SU-8 hinges. The photoresist was baked for a longer time to drive away the remaining solvents but the problem of the bubbles still didn't go away. Figure 30 shows a large bubble in the thick OCG 825 layer which has spread into the anchor regions.

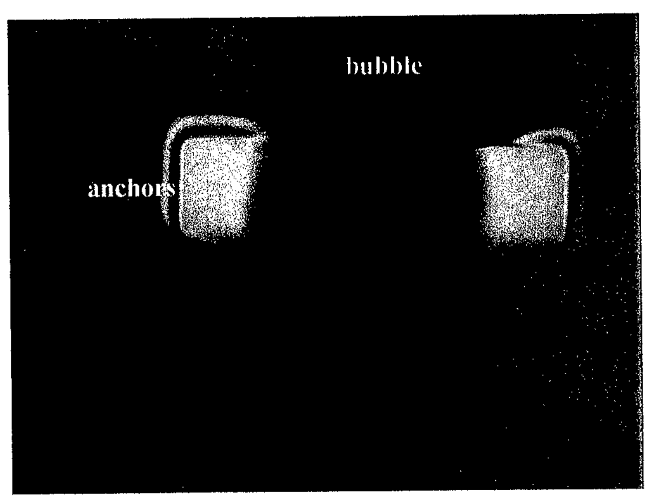


Figure 30: Image showing the appearance of a bubble on a thick photoresist layer.

Later it was determined that having the bubble just over the pin structure was actually advantageous for the following reasons:

- The bubble created a large enough space between the photoresist and the SU-8 hinges for the mirror to rotate freely.
- This extra gap provided additional clearance for the solvents to penetrate into tight spots.

In fact, having the bubble over the pin structure turned out to be critical because it proved to be very difficult to release the SU-8 hinges at the places where no bubble was present. However, it was equally important to contain the size of the bubble so that it wouldn't spread into the anchor regions and result in the formation of weakened hinge structures.

We were able to contain the size of the bubble by using a combination of two different spin rates when applying OCG 825 photoresist. First, the photoresist was spun at 90 rpm for 30 secs and baked at 90°C for 45 mins. For the next coat, the photoresist was spun at 4000 rpm for 30 secs and baked at 90°C for 45 secs. This combination of the two different spin rates resulted in a much improved shape of the bubble as shown in the Figure 31.

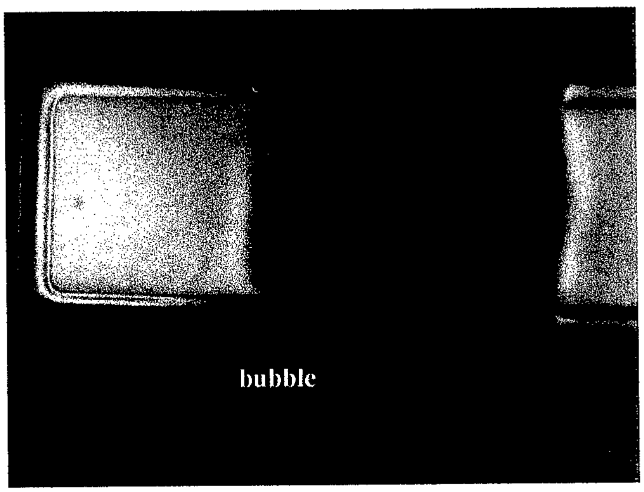


Figure 31: Improving the coating technique of the OCG 825 photoresist resulted in more controlled shape of bubble.

Since the purpose of the thick layer of photoresist was only to create a spacer layer between the photoresist and the SU-8 structures, the photoresist didn't need to be hard baked. Later on, it turned out that the hard baking of the photoresist had hardened the photoresist to the extent that it was quite difficult to dissolve. We know that solvents like acetone and EMT can dissolve hard baked photoresist. However, it was found that use of these solvents has an adverse effect on the SU-8 structures: SU-8 structures started to delaminate from the anchor points.

After forming the anchors in the photoresist layer, the wafer was placed in the BOE solution for one minute in order to completely remove any traces of native oxide from the anchor surface. The wafer was rinsed, cleaned and dried thoroughly. Figure 32 shows anchors after patterning the thick photoresist. Figure 33 shows the coverage of the OCG 825 photoresist on the mirror structure and the deep trenches.

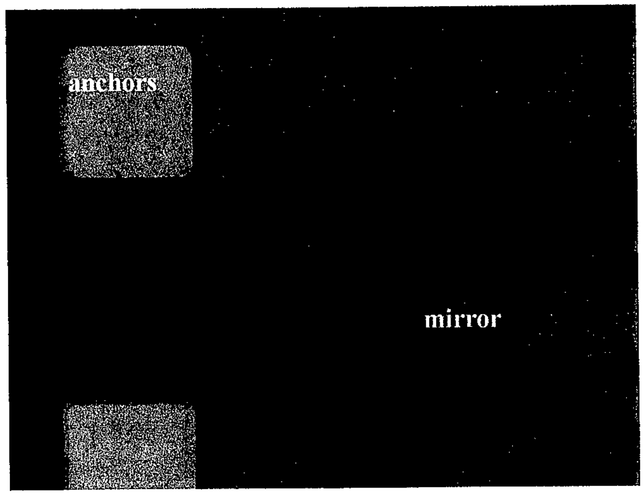


Figure 32: Image of the anchor after the patterning of the thick photoresist.

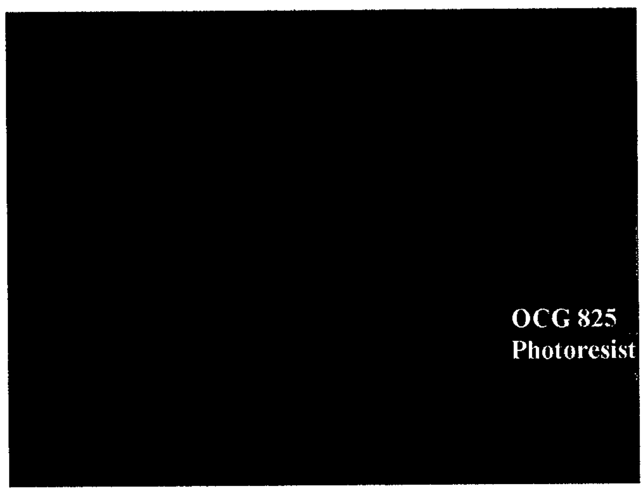


Figure 33: Coverage of thick layer of the OCG 825 photoresist on the mirror structures and the trenches.

## 5.7 Fabrication of SU-8 Hinges

SU-8 is a negative photoresist supplied by MicroChem Corp (MCC). It is a relatively new photoresist and used mainly in fabricating MEMS structures with a high aspect ratio. Although much of the characterization work of SU-8 is still in progress, researchers have been exploiting the mechanical properties of this photoresist to make simple mechanical structures. SU-8 can be spun to thicknesses from 1 – 1000 μm using a single coat. It can be exposed with 350 – 450 nm UV broadband radiation and patterned using standard MEMS processes. High aspect ratios in thick SU-8 films with smooth vertical sidewalls are possible. Once hard baked at 200°C, SU-8 can withstand harsh etchants like hydrofluoric acid and reactive ion etching. Information on processing of SU-8 is available on MicroChem's Internet bulletin board:

http://www.microchem.com. SU-8 in liquid form is sold in different grades: SU-8 (10) was chosen because of its thickness characteristics.

These excellent properties of SU-8 photoresist were the primary reason why we wanted to try it in making the required hinges. There were two more advantages in using SU-8 for making hinges: 1) SU-8 resist can easily be spun on top of the OCG 825 layer, and 2) all the necessary chemicals and materials for the SU-8 processing were available in-house.
SU-8 (10) photoresist was spun on top of the already existing OCG 825 layer at 640 rpm for 30 secs. The photoresist was baked first at 68°C for 5 mins and then at 95°C for 30 mins to remove all the solvents from the photoresist. Before removing the wafer from the oven, the wafer was cooled to 55°C to prevent stress-generated cracks in the SU-8 layer. Thickness of the SU-8 layer was 40 μm. Figure 34 shows the deposition of the thick SU-8 layer on top of the OCG layer. The square regions are anchors for the hinge. Haziness at the edges of the anchors is due to the thick SU-8 layer.

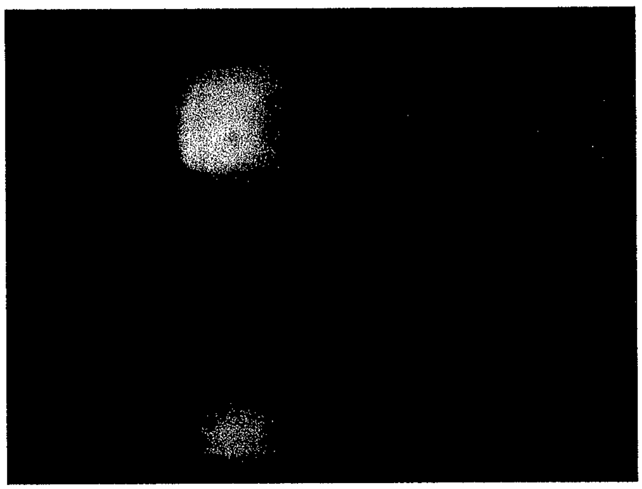

Figure 34: Thick SU-8 deposited on the OCG 825 photoresist.

The SU-8 layer was exposed with UV in the photo aligner for 90 secs. The wafer was then placed in the clean room oven at 95°C for 90 secs as a post-exposure-bake. The wafer was cooled to 68°C before being removed from the oven. The SU-8 was then developed in an SU-8 developer (supplied by MCC) for 5 mins. To remove any excess SU-8 from the wafer surface, the wafer was rinsed in an SU-8 thinner solution (also supplied by MCC) for 30 secs. The wafer was then rinsed with the de-ionized water and dried very carefully.

The quality of SU-8 structures from the initial set of wafers were not satisfactory. Adhesion of the SU-8 hinges at the anchor places was poor and as a result delaminated during the rinsing and cleaning. On close inspection, it appeared that the SU-8 hinges were severely undercut after development which may have caused poor adhesion of the photoresist to the anchors. This may have occurred due to the following possible reasons: 1) over-exposure to UV, 2) over development of the SU-8, or 3) insufficient baking of SU-8.

Several experiments to optimize exposure and development of SU-8 photoresist were performed. Exposure time was varied between 15 to 90 secs keeping the thickness of the SU-8 layer constant. Developing time was varied between 3 to 5 mins. Post-exposure baking was performed at 95°C as recommended by MCC, however, baking time was varied between 90 sec to 60 mins. After the experiments, it was concluded that for a 40 μm thick SU-8 layer, the optimum numbers were: 20 secs of UV exposure, post-exposure bake at 95°C for 30 mins, and cooling to 68°C before removing from the oven, 3 mins in the SU-8 developer and immediately followed by a 30 secs dip in SU-8 thinner. SU-8 photoresist processed with these numbers resulted in structures with significantly superior adhesion.

As mentioned previously, the remaining solvents from the underlying OCG 825 photoresist started to appear in the form of bubbles as soon as the wafer was placed in the oven for post-exposure baking of the SU-8 photoresist. We also noted that these bubbles appeared only at the places where the OCG 825 photoresist was exposed by UV during SU-8 exposure, i.e., the region between the anchors as shown in the Figure 31. As mentioned previously, the formation of the bubble turned out to be an extremely useful feature at the time when the hinge structures were ready for final release. The formation of a bubble underneath the SU-8 layer forced the SU-8 layer to form a bridge-shaped structure on top of the pin structure. This shape produced a gap between the mirror and the hinge structures required to rotate the mirror freely. We were able to control the size and the position of the bubble by optimizing the OCG 825 photoresist deposition technique.

Another interesting event occurred during the development of the SU-8 photoresist. While the SU-8 material was being developed, the underlying OCG 825 layer also fully dissolved in the developer. This side effect too turned out to be a favorable one. Due to this, it was not necessary to dissolve the underlying OCG 825 layer separately in any other solvent such as acetone or EMT. Had the acetone or EMT been used to dissolve the underlying OCG 825 layer, the SU-8 structures would have been severely attacked by these solvents. This was an important discovery. Figure 35 shows an SU-8 hinge structure after the development of SU-8 material.

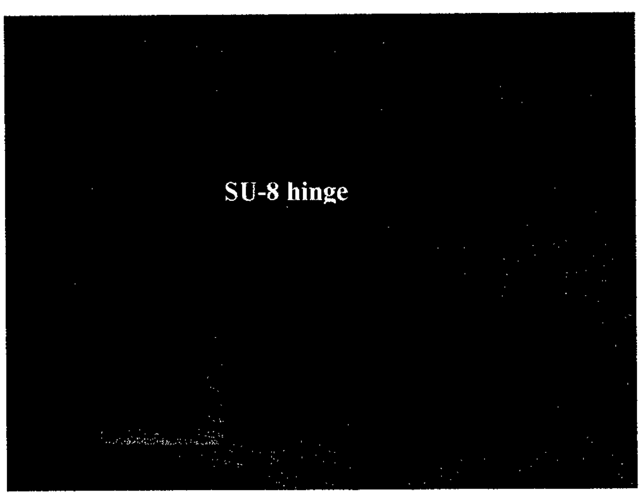


Figure 35: Developed and released SU-8 hinge structure.

To get the best mechanical properties from SU-8 material, the SU-8 structures were hard baked at 200°C for 30 mins. It was important to cool the wafer to around 60°C before pulling the wafer out of the oven. Once hard baked, the SU-8 hinges acquired their permanent shape and their resistance to harsh chemicals such as HF. The structures were very closely inspected after SU-8 development to ensure that there were no traces of remaining SU-8 photoresist left near the hinge structures or in the trenches. After hard baking any traces of the leftover SU-8 photoresist are impossible to remove or dissolve. After hard baking, the adhesion of hinges with anchors improved dramatically. Figure 36 shows the SU-8 hinge structure after hard baking at 200°C. The Figure 36 clearly indicates that the underlying OCG 825 layer has been dissolved between the mirror and the SU-8 hinge structure.

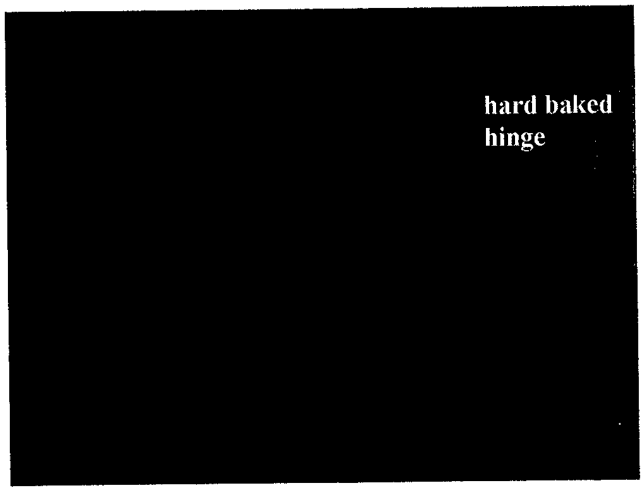


Figure 36: The SU-8 hinge structure after hard baking at 120°C. Also shows that underlying the OCG layer has been completely dissolved.

### 5.8 Release of Mirrors

Attempts were made to release the mirror structures on the wafer. This required the removal of the sacrificial layer of silicon oxide on the SOI wafer. This oxide layer is about 1.5 μm thick and must be etched away laterally at least 10 μm. HF (48%) or the buffered oxide etchant were used to etch away the silicon oxide layer.

Using BOE, the normal rate for the removal of the thermally grown oxide on the surface of a wafer is about 1 μm per 10 minutes, suggesting that the final releasing of the mirrors will require a long time. By contrast, in the HF solution, the normal rate of oxide etch is about 3 μm per minute--it would take only 3 mins in the HF solution to completely release the mirrors. In a separate set of etching experiments, the release times for the mirror structures in both etchants were determined:

- The HF 48% solution took about 3 mins to release the mirrors completely.
- The BOE took about 45 mins to release.

In the first few mirror release experiments the results were not encouraging. The HF solution, though fast in removing silicon oxide, aggressively attacked near the hinge anchors and as a result dislodged the hinges from the anchors. BOE, which contains HF and a PH buffer, didn't attack the anchors as aggressively and was slow in removing the silicon oxide. Thus the immediate problem was to improve the adhesion of the SU-8 hinges with the anchors.

Several experiments were planned in order to improve adhesion of the SU-8 hinges with the anchors. According to the published SU-8 literature, adhesion of SU-8 photoresist can be enhanced by optimizing the post-exposure bake process. A set of experiments with variations in the post-exposure baking time were performed. The results are set forth in the following table:

| Baking time | Release in HF 48% | Release in BOE |
|---|---|---|
| At 95°C for 90 secs | Hinges delaminated in < 2 mins | Hinges delaminated in 10 mins |
| At 95°C for 15 mins | Delaminated in 2 mins | Delaminated in 30 mins |
| At 95°C for 30 mins | Delaminated after 3 mins | Delaminated after 45 mins |
| At 95°C for 45 mins | Delaminated after 3 mins | Delaminated after 45 mins |

Table 1: Effect of post-exposure baking time on SU-8 hinge-anchor adhesion.

We also believed that the removal of the hinge structures in the oxide etchant could be due to the presence of a thin layer of native oxide on the anchors. An experiment was performed to verify this theory. A wafer (with mirror structures) was placed in the BOE solution for 1 min to remove the native oxide layer just before spinning the SU-8 photoresist.

Encouraging results were obtained by 1) removing the native oxide layer through immersion of the wafer in BOE for 1 min just before SU-8 deposition, and 2) using the optimized post-exposure baking procedure for the SU-8 photoresist. After these modifications in the processes, we were able to release the mirror structures in HF solution in about 3 mins without destroying the hinges. That was an important accomplishment as far as the fabrication of the device was concerned.

Figure 37 shows that the mirror structures have been released completely.

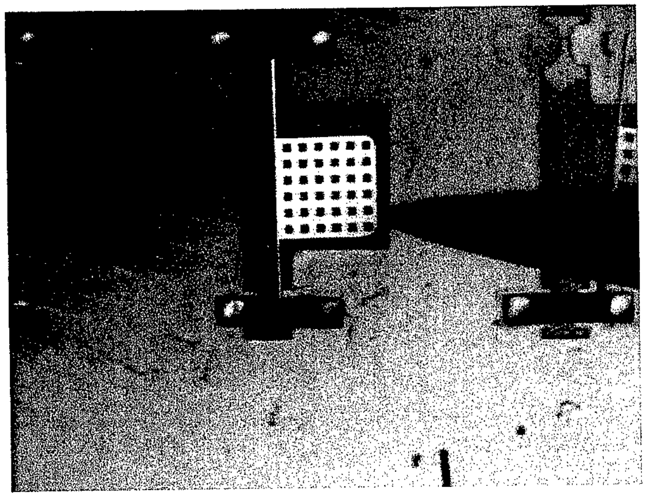

Figure 37: The mirror structure and the hinge structures after releasing.

### 5.9 Tilting of Mirrors

In this phase of the research work, the emphasis was to determine whether mirrors, as fabricated, could be raised so as to prove the functionality of the SU-8 hinge structures. For this work an enhanced capability in viewing and manipulating the micromirrors was necessary.

An in-house micromanipulator designed for this purpose was used. The micromanipulator consists of an X-Y stage (type MicroControle – made in France) mounted on a platform which is rigidly attached to a Nikon metallurgical microscope. Mounted on the same base are two 3-axis micropositioner stages (Edmund Scientific, Type Fine Screw, Catalog No. A38,528). Each micromanipulator has a microprobe attached (Lucas/Signatone Corp., Type SE-TB or SM-10). The sample wafer, which is fastened to the X-Y stage, can be moved into position under the microscope's optic axis, and each of the two probes can be independently manipulated to operate the levers at the other end that can be used in moving a micro-objects.

With this device it is feasible to move, in micro-scale increments, objects a few microns in size. Levers can be tilted by putting a microprobe under the edge and lifting the microprobe.

A Panasonic color video camera and a frame grabber was used to capture and store digitally images of the moving mirrors.

Using the micromanipulator, a group of hinged mirrors were raised from a horizontal to a vertical position. Figures 38 to 42 illustrate the sequence of raising the mirror structures using microprobes.

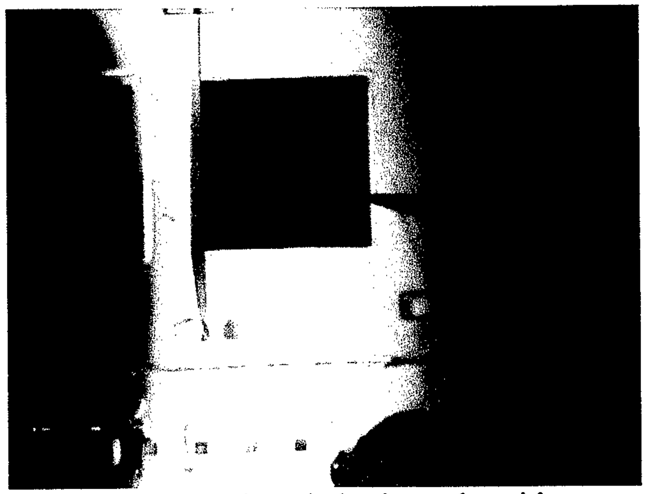
Figure 38: Mirror in horizontal position.

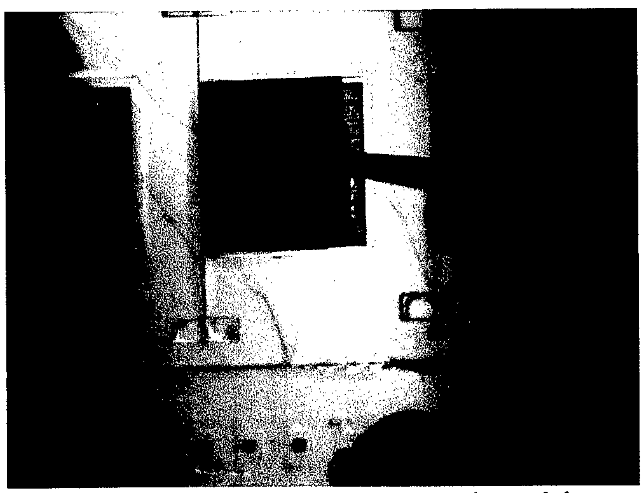
Figure 39: Using the micromanipulator probe, raising a mirror.

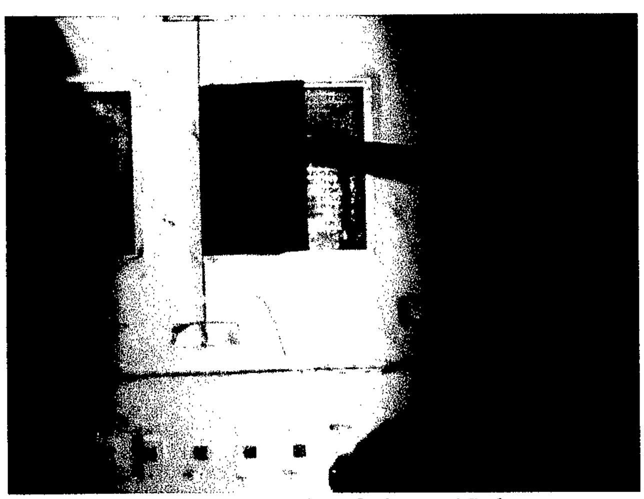
Figure 40: Tilt angle of about 45 degrees.

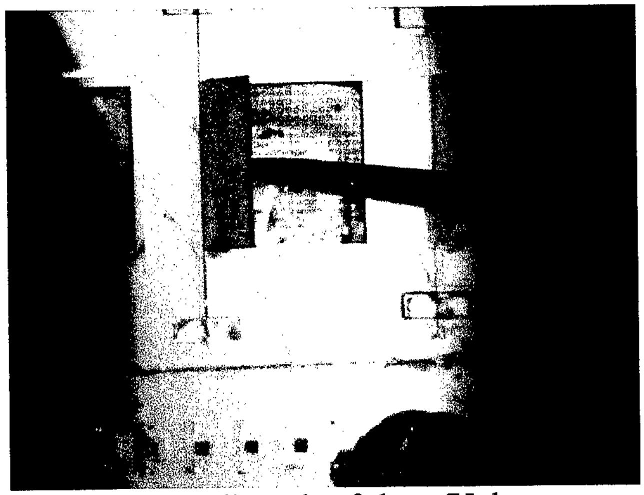

Figure 41: Tilt angle of about 75 degrees.

Figure 42: Mirror raised to vertical position.

## 5.10 Detailed list of Process Steps

A majority of all processes used in the microfabrication of mirrors, hinges and actuators have been reduced to routine. A run-sheet listing all processing steps has been created. A copy of this run-sheet is included as Appendix A.

## 6.0 PROPOSED FOLLOW-ON RESEARCH AND DEVELOPMENT

Although a number of goals for this project were accomplished as described above, more needs to be done to fabricate a complete device system. The mirror structures must be actuated either by shape memory alloy or magnetically. To get shape memory actuation, appropriate beam structures incorporating TiNi thin film need to be designed and fabricated. The design of the actuator should be such that TiNi thin film, when heated electrically, will lift the beam structure to a vertical position. The thickness of the TiNi thin film determines the amount of force with which the beam structure is actuated. Once the mirror has been actuated to vertical position, it needs to be latched at that position.

A latching mechanism must to be incorporated into the mirror design. For instance, in the fiber optic switch application, the mirror must be latched securely in a vertical position in order to deflect a light beam from a fiber in the same plane. To get a reversible displacement of the mirror, the mirror must be de-latched and actuated back to the horizontal position. Another set of shape memory actuators is required in order to release the mirror from the latching mechanism to move the mirror back to the horizontal position. The shape memory actuator and the latching mechanisms have been designed on a preliminary basis and are shown in Figure 17. Further work needs to be done to determine whether the design is functional. The actuator structure must be designed such that it allows reversible displacement (horizontal to vertical and then back to the horizontal) of the mirror.

In general, a shape memory alloy can be deformed up to 3 to 4% and can be recovered fully when released. This cycle of large deformation and full recovery in SMA can be repeated for several millions of cycles. To exploit the SMA to such an extent, the material must first be pre-strained by 3 to 4%. Such strain recovery of the SMA thin film can also be used in deflecting the mirrors but this would require pre-straining the film by 3 to 4%. Although pre-straining of TiNi thin film, which has its dimensions in micrometers, is quite tricky it has been proven possible.

In the future designs, some pre-straining mechanisms for the TiNi thin film should also be included. Microprobes can be used for pre-straining the TiNi thin film.

## 7.0 UPDATED COMMERCIALIZATION PLANS AND RECOMMENDATIONS

According to a recent study by a market research firm Venture Development Corp. (VDC), published in the *Micromachine Devices* July 2000 issue, the market for optical micromirror switches can be expected to grow rapidly. [11]. The report projects overall market size to be between $4 - 7 billion in 2004. In the past 3 years, several companies have emerged to take advantage of the tremendous opportunity.

Most major players that are actively developing fiber optic switches are pursuing switch designs based on micromirrors. Piezoelectric, electrostatic, electromagnetic, bimetallic principles are being used for the actuation of the mirrors. Since shape memory alloy produces a much larger work output per unit volume of the material (compared to any other actuation method) we believe that the thin film shape memory alloy is extremely suitable for the development of a smaller, stronger and faster switch.

During 2000, the company licensed its thin film shape memory alloy technology to Optimems, Inc. in return for a major equity share in that company. Due to the recent downturn in the economy, Optimems, Inc has not been able to raise funds to pursue the development of the fiber optic switches; however, there has been a significant interest in the fiber optic community to explore the use of the shape memory actuation for switching of the mirrors. Several companies have approached us in the past year and have discussed the possibilities in length.

Another fiber optic device, a variable optical attenuator (VOA), has been a subject of interest in the past few months. The VOA is a shutter type device which is used to regulate the size of a collimated light beam coming out of an optical fiber. One of the requirements for the VOA is that the shutter must be able to move into and out of the optical beam in an incremental fashion. This requires a rachet mechanism. The shutter and the rachet mechanism can be built using silicon micromachining. TiNi thin film can be used for the displacement of the shutter and rachet. Copley Networks based in Los Angeles, a fiber optic systems manufacturer, has shown a definite interest in the development of the VOA device based on the shape memory alloy. Further discussion on this development work is currently in progress.

## 8.0 REFERENCES


[1] William P. Taylor, M. Schneider, H. Baltes, M. G. Allen, "*Electroplated Soft Magnetic Materials for Microsensors and Microactuators*", IEEE Transducers '97, International Conference on Solid-State Sensors and Actuators, Chicago, June 16 – 19, 1997

[2] V. Raman, M. Pushpavanam, B. A. Shenoi, *"Some Property Data for Nickel-Iron Alloy Electrodeposits*", Plating and Surface Finishing 1982, p-132 – 136

[3] J. Y. Park, M. G. Allen, "*Electroplated and Screen-Printed magnetic Materials Applicable to Micromachined magnetic Devices*", SPIE Conference on Materials and Device Characterization in Micromachining, Santa Clara, CA, September 1998, p-154 - 167

[4] Yong Yi, Chong Liu, "*High Yield Assembly of Hinged 3-D Optical MEMS Devices using Magnetic Actuation*", SPIE, Santa Clara, CA Septmeber 1998, pp 125-134

[5] L.Y. Lin, S.S. Lee, M.C. Wu, K.S.J Pister, Micromachined Integrated Optics for Free-Space Interconnections, MEMS Workshop, Amsterdam, January 1995, IEEE Catalog Number 95CH35745.

[6] W.-H. Juan and S.W. Pang, "High Aspect Ratio Si Vertical Micromirror Arrays for Optical Switching", JMEMS Vol. 7 No. 2 June 1998, pp 207-213.

[7] A. Friedberger and R. Muller, "Improved Surface-Micromachined Hinges of Fold-Out Structures",JMEMS Vol. 7 No. 3 September 1998, pp 315-319]

[8] M.Fernandez, E. Kruglick, MEMS Brings New Solutions to Photonic Switching, Optical Micro-Machines Inc. San Diego.

[9] M. Wuttig, Q. Su, Composite Shape Memory Micro Actuator, U.S. Patent Number 5,825,275, Oct.1998.

[10] "*SU-8 Bulletin Board*" Information on the SU-8 photoresist posted on the Internet by MicroChem Corp. http://www.microchem.com

[11] "Micromachine Devices" An R&D Magazine on MEMS activities around the world, July 2000 issue Vol. 5, No. 7, page 10

## APPENDIX A

### Process sequence for Micro-mirror and hinges

| No | Process Description | Remarks/Comments |
|---|---|---|
| 1 | Use SOI wafer with alignment marks on both sides of the wafer. | |
| 2 | spin OCG 825 4k rpm 30 sec 2 coats both sides | |
| 3 | soft bake 90C 30 mins | |
| 4 | UV expose handle wafer side with "Wet Etching Mask" 30 secs. Note that dry etching part of this mask need to be covered with an Al foil. | |
| 5 | Develop in OCG809 2 mins. Rinse and dry. Determine development time. | |
| 6 | hard bake 120C 30 mins | |
| 7 | Blue tape on membrane side | |
| 8 | In BOE for oxide pattern. Determine the etching time in BOE (approx 12 mins). Remove blue tape. | |
| 9 | In EMT 80C 20 mins to strip OCG 825. rinse and dry well. | |
| 10 | Sputter Cr (500A) on membrane side for protection of oxide in KOH. Use Perkin Elmer sputtering system) | |
| 11 | In KOH 30% 52C until the etch stops (automatic stop) | |
| 12 | In Cr etch to remove Cr from front side. Rinse and dry well. | |
| 13 | Bond plain wafer on back side. Spin 4krpm 10 sec. Bake 110C 30 mins. | |
| 14 | spin OCG 825 4k rpm 30 sec 2 coats front side only | |
| 15 | soft bake 90C 30 mins | |

| | | |
|---|---|---|
| 16 | UV expose front side with "Mirror Mask" 30 secs | |
| 17 | Develop in OCG809 2 mins. Rinse and dry. | |
| 18 | hard bake 120C 30 mins | |
| 19 | In BOE for oxide pattern. Remove bonded wafer from back side in EMT 80C. Rinse and dry. | |
| 20 | In KOH 52C until the etch stops (automatic stop) | |
| 21 | PE: Sputter etch 500W RF 3 mins. Sputter Cr front side. Thickness about 500 - 1000A | |
| 22 | Bond plain wafer on back side. Spin 4krpm 10 sec. Bake 110C 30 mins. | |
| 23 | spin OCG 825 4k rpm 30 sec 2 coats front side only | |
| 24 | soft bake 90C 30 mins | |
| 25 | UV expose front side with "Anchors Mask" 20 secs | |
| 26 | Develop in OCG809 2 mins. Rinse and dry. | |
| 27 | hard bake 120C 30 mins | |
| 28 | In Cr etch to pattern Cr. Rinse and dry well. | |
| 29 | Remove bonded wafer from back side in EMT 80C. Rinse and dry well. | |
| 30 | PE: Sputter etch 500W RF 3 mins and then Sputter TiNi 4-5 microns. | |
| 31 | NRC2: Anneal TiNi at 500C. | |
| 32 | Bond plain wafer on back side. Spin 4krpm 10 sec. Bake 110C 30 mins. | |
| 33 | spin OCG 825 4k rpm 30 sec 2 coats front side only | |
| 34 | soft bake 90C 30 mins | |

| | | |
|---|---|---|
| 35 | UV expose front side with "TiNi Mask" 30 secs | |
| 36 | Develop in OCG809 1.5 mins. Rinse and dry. | |
| 37 | hard bake 120C 30 mins | |
| 38 | In TiNi etch to pattern TiNi. Determine etch rate. Rinse and dry well. | |
| 39 | Remove bonded wafer from back side in EMT 80C 20 mins to strip OCG 825. rinse and dry well. | |
| 40 | Blue tape to cover TiNi actuators region on wafer for protection. Blue tape on back side (whole). | |
| 41 | In TiNi etch to remove left over TiNi from cavities around mirror. Determine etch rate. Rinse and dry well. | |
| 42 | Remove blue tape in acetone and then clean wafer in EMT 80C. Rinse and dry well. | |
| 43 | Bond plain wafer on back side. Spin 4krpm 10 sec. Bake 110C 30 mins. | |
| 44 | Fill/Spin OCG825 front side. Only in spin mode at 90 rpm 35 secs 3 coats. | |
| 45 | soft bake 90C 30 mins | |
| 46 | UV expose with "Anchors Mask" 60 secs. | |
| 47 | Develop in OCG 809 2 mins. Rinse and dry well. | |
| 48 | hard bake 120C 30 mins | |
| 49 | In Cr etch for Cr patterning. | |
| 50 | In BOE for oxide patterning for hinge anchors and SU8 connector hinges. | |

| | | |
|---|---|---|
| 51 | Remove blue tape very carefully. Note that we want to keep the patterned OCG at the front side. Also investigate to see if wafer can be loaded into PE with blue tape on the back side. | |
| 52 | Sputter Cr 500-1000A front side on top of OCG 825. | |
| 53 | Blue tape on back side. | |
| 54 | spin OCG 825 4k rpm 30 sec 2 coats front side only | |
| 55 | Soft bake 90C 30 mins | |
| 56 | UV expose front side with "Anchors Mask" again 20 secs | |
| 57 | Develop in OCG809 2 mins. Rinse and dry. | |
| 58 | hard bake 120C 30 mins | |
| 59 | In Cr etch for Cr patterning. Rinse and dry well. | |
| 60 | Leave OCG 825 on front side since removing that may cause removal of underlying OCG layer. | |
| 61 | Spin SU8. Determine spin speed, time, procedure etc. | |
| 62 | Prebake SU8. Determine temp, time etc. | |
| 63 | UV expose SU8 with "SU8 Mask". Determine exposure time. | |
| 64 | Post bake SU8. Determine temp, time etc. Note that NO HIGH TEMP CURING AT THIS POINT. | |
| 65 | Strip OCG/Cr/OCG/Cr from underneath SU8 bridges until their release. Use hot EMT and Cr etchant. Record all timings. | |
| 66 | Final Curing of SU8. Determine the procedure. | |

| | | |
|---|---|---|
| 67 | Final oxide etching from both sides to release devices. Not sure if a) front side should be protected from BOE/HF by black wax, 2) steps 62 & 63 should be performed after or before this oxide release step. | |
| | **The following steps were added to the above as a temporary change** | |
| | In step#65, it had become almost impossible to remove OCG from the surface. Boiling hot EMT worked but that removed SU-8 also. Cleaned the wafer in hot EMT very well. | |
| 68 | Bonded wafer on a plain wafer as instructed above | |
| 69 | Spun OCG 825 90 rpm 35 sec 3 coats for filling the space for hinge fabrication. Soft bake at 90C 30 mins after each coat (otherwise bubbles from solvent will ruin OCG coat) | |
| 70 | Patterned thick OCG with "Anchors" mask as in steps 46 through 48. | |
| 71 | Process SU-8 as in steps 61-64. | |